Grant Agreement Number:
657263

Action acronym:
GATEWAY

Action full title:
Developing a Pilot Case aimed at establishing a European infrastructure project for CO_2 transport

Type of action:

H2020-LCE-19-2014-2015

Starting date of the action: 2015-05-01
Duration: 24 months

D4.3
PCI prospectus – business case development

Original due delivery date: 2017-03-31
(Amended with European Commission Approval to 30 April 2017)
Actual delivery date: 2017-05-02

Organization name of lead participant for this deliverable:

TNO

This project is funded by the European Union

Project funded by the European Commission within Horizon2020		
Dissemination Level		
PU	Public	x
CO	Confidential , only for members of the consortium (including the Commission Services)	

Deliverable number:	D4.3
Deliverable title:	PCI prospectus – business case development
Work package:	WP4 Task4.4
Lead participant:	TNO

Author(s)		
Name	**Organisation**	**E-mail**
Tom Mikunda	TNO	Tom.mikunda@tno.nl
Filip Neele	TNO	Filip.neele@tno.nl

Abstract

The GATEWAY has developed a pilot case that could form the first part of a large-scale, international CO_2 transport and storage network. The GATEWAY pilot case is the ‘Rotterdam Nucleus’, a mostly offshore transport pipeline that connects several CO_2 sources (emitters in the Rotterdam industrial region, as well as offshore gas separation facilities) with offshore storage capacity of several hundreds of megatonnes in multiple locations. The Rotterdam Nucleus has been submitted as a potential Project of Common Interest (PCI), in the framework of the Trans-European Networks for Energy (TEN-E) regulations, in April 2017.

This report presents the document that was used to submit Rotterdam Nucleus PCI. The lay-out of the pipeline structure is presented, based on current status of CO_2 emissions in the Rotterdam harbour, on current initiatives for reducing the greenhouse gas emissions from the industrial area. The scope for future growth is sketched, both on the CO_2 supply side, with both Antwerp and Germany potentially connecting to the offshore network through Rotterdam, and on the storage side, with vast storage capacity of the North Sea at close range from the Rotterdam Nucleus pipelines.

This project is funded by the European Union

TABLE OF CONTENTS

Page

This project is funded by the European Union

1 INTRODUCTION

The GATEWAY has developed a pilot case that could form the first part of a large-scale, international CO_2 transport and storage network. The GATEWAY pilot case is the ‘Rotterdam Nucleus’, a mostly offshore transport pipeline that connects several CO_2 sources (emitters in the Rotterdam industrial region, as well as offshore gas separation facilities) with offshore storage capacity of several hundreds of megatonnes in multiple locations. The Rotterdam Nucleus has been submitted as a potential Project of Common Interest (PCI), in the framework of the Trans-European Networks for Energy (TEN-E) regulations, in April 2017.

This report presents the document that was used to submit Rotterdam Nucleus PCI. The layout of the pipeline structure is presented, based on current status of CO_2 emissions in the Rotterdam harbour, on current initiatives for reducing the greenhouse gas emissions from the industrial area. The scope for future growth is sketched, both on the CO_2 supply side, with both Antwerp and Germany potentially connecting to the offshore network through Rotterdam, and on the storage side, with vast storage capacity of the North Sea at close range from the Rotterdam Nucleus pipelines.

The Rotterdam Nucleus PCI was submitted by the Rotterdam Port authority, with several industrial parties as affiliated partners.

The complete PCI submission document is presented below, in Sections 2 to 4. The structure of the submission template is followed closely.

This project is funded by the European Union

2 PART A: GENERAL INFORMATION

2.1 A.1 general project information

a) Title of project

The Rotterdam Nucleus

b) Type of project / infrastructure priority

EU 347/2013, Annex II.4[1]

i. *Dedicated pipelines, other than upstream pipeline network, used to transport anthropogenic carbon dioxide from more than one source, i.e. industrial installations (including power plants) that produce carbon dioxide gas from combustion or other chemical reactions involving fossil or non-fossil carbon-containing compounds, for the purpose of permanent geological storage of carbon dioxide pursuant to Directive 2009/31/EC of the European Parliament and of the Council*[2]*.*

   Relevant for project: The project involves dedicated pipelines used to transport CO_2 from a coal-fired power plant and nearby industrial locations and from offshore natural gas processing facilities for geological storage according to Directive 2009/31/EC.

ii. *Facilities for liquefaction and buffer storage of carbon dioxide in view of its further transportation*[3]*.*

   Potentially relevant for future expansion of the project, however not included in current version of the Rotterdam Nucleus.

iii. *Any equipment or installation essential for the system in question to operate properly, securely and efficiently, including protection, monitoring and control systems.*

   Relevant for project: Compression, safety and monitoring equipment is needed for the operation of the CO_2 pipelines.

c) Countries involved

Member States or Member State and EEA country involved. Note: the plan for the project development must involve at least two Member States or one Member State and one EEA country (see also EU 347/2013, 4.1.c). This plan is to be presented to the European Commission separately in order for the PCI application to proceed.

---

[1] See also CBA Methodology Report Sections 3.1.2, 3.1.3

[2] OJ L 140, 5.6.2009, p. 114.

[3] This does not include infrastructure within a geological formation used for the permanent geological storage of carbon dioxide pursuant to Directive 2009/31/EC and associated surface and injection facilities.

This project is funded by the European Union

The Netherlands
The United Kingdom

Not part of this application, but likely to be affected as a result of construction of this new infrastructure: Belgium and possibly Germany.

d) Description of the context for the project

To make significant and cost-effective CO_2 emission reductions from large European industrial clusters, deploying CO_2 capture, transport and storage (CCS) will be unavoidable. The vast majority of conventional industrial production processes, such as refining, basic chemical production and steel-making have reached their thermodynamic limits of energy efficiency. For many of these industries, CO_2 capture is the only technology that can be retrofitted to existing assets to improve their carbon footprint. The limits to energy efficiency and electrification of industrial processes means that CO_2 capture will be needed until new re-engineered processes and low-carbon materials are available to society.

Despite strong growth in the deployment of renewable energy technologies in Europe, the total gross consumption of renewable power across the 28 Member States is currently around 16% (Eurostat, 2017). The EU Reference Scenario 2016 suggests that the share of renewables in the EU energy mix will continue to grow, from 21% in 2020 to 24% in 2030 and 31% in 2050 (European Comission, 2016). However, this will not be sufficient to contribute to meeting the agreed longer term climate targets of a 80-95% reduction in CO_2 compared to 1990 levels. Without dramatic shifts in policy to greatly accelerate the deployment of renewables with energy storage, CCS will remain a key mitigation solution across both the industrial and power sectors. Particularly for countries such as the Netherlands (5.5% renewable power), Belgium (8%), the UK (7%) and Germany (14%), power generation from thermal combustion of coal and gas remains the backbone of their energy systems. In non-EU ETS sectors too, such as municipal waste incineration, CCS can make a considerable contribution to the reduction of total national emissions.

Although a number of operators in the power and industrial sectors across Europe have explored the integration of CO_2 capture into their processes, the development of full-chain CCS projects, particularly the operation of transport and storage facilities, is often considered out-of-scope of their normal business practices. In this light, particularly for large-scale multi-user CO_2 infrastructure, new enterprises, consisting of commercial and non-commercial entities with the relevant expertise, access to capital, and ability to manage potential risks and liabilities will be needed to invest in and operate such infrastructure.

CCS as a technology, presents a number of logistical challenges, and access to safe and secure geological storage sites is an obvious condition. Research using existing geological information has indicated with a relatively high degree of confidence, that formations with suitable characteristics for the permanent storage of CO_2 are distributed heterogeneously

This project is funded by the European Union

across Europe. Countries with considerable natural gas reserves, such as the UK, The Netherlands and Norway, have good access to potential CO_2 storage sites as the same geological traps that have held natural gas in place for geological time, can in principle be re-used to store CO_2.

For certain Member States, such as Belgium, there are no possibilities for storage in natural gas fields, and the exploration state of sandstone aquifers is poor (Rütters, 2013). Negative public opinion regarding the process of CO_2 storage has led to a number of political decisions being made to prohibit the onshore storage of CO_2 in certain Member States, for example in Germany, which further delineates where CO_2 storage sites could be developed. Therefore for certain Member States with an interest in deploying CCS, but which either lack the suitable geology, or have planning restrictions in place, cross-border CO_2 transport infrastructure will be necessary.

The North Sea Basin Task Force (NSBTF), a group of public and private bodies aiming to develop common principles for managing and regulating the transport, injection and permanent storage of CO_2 in the North Sea, have informed the European Commission of possible CO_2 infrastructure needs. The 'North Sea sub-seabed strategic regional plan on CCS transport infrastructure' from February 2017 (NSBTF, 2017), highlights a number of potential Project of Common Interest concepts, which it describes as "sensible locations for initial infrastructure development". The development of a CO_2 hub at the Port of Rotterdam, with links to the Port of Antwerp and the North Rhine Westphalia region, is one of the concepts that is showcased. The NSBTF plan emphasizes the link between the Dutch and UK offshore areas, as is illustrated in the map in Figure 1.

The Port of Rotterdam is the largest seaport in Europe with an annual throughput of goods of around 465 million tonnes in 2015. The port area stretches over 40 km from the City of Rotterdam to the Maasvlakte 2 area, which projects into the North Sea. The Port of Rotterdam provides direct employment for 90 000 people. The port area includes about 6,000 ha of industrial sites, with considerable refining and petrochemical sectors, in additional to two large coal-fired power stations and an industrial waste incinerator. These activities create considerable CO_2 emissions, a total of 30.3 $MtCO_2/a$, which equals 18% of the total CO_2 emissions of the Netherlands (Wuppertal Institute for Climate, 2016). In 2016 the Port of Rotterdam Authority commissioned a report to identify possible decarbonization pathways for the area. In the majority of the possible decarbonization pathways, the use of CCS in the refining, petrochemical and power sectors was unavoidable in making deep emission cuts (80%+ against 1990 levels) in the port before 2050 (Wuppertal Institute for Climate, 2016).

The Port has long standing ambitions for developing industrial scale CCS projects. CO_2 is currently transported through part of the port area through the 'OCAP' pipeline. The OCAP pipeline transports approximately 400 $ktCO_2$ per year from two pure CO_2 sources (a refinery and a bioethanol plant) to support crop growth in greenhouses to the north of Rotterdam. The demand for CO_2 from the greenhouses is only during the summer months, which means considerable CO_2 can be sent for geological storage during the winter months. In 2011, the ROAD

CCS Project, was announced, which would capture 1.1 $MtCO_2$/year from a newly constructed capture ready coal-fired power station in the most western part of the port area adjacent to the North Sea. The proposed start of operation of ROAD was 2015, however the project has experience considerable delays partly due to the drop in the cost of emitting carbon (EU ETS) in Europe since 2011. In recent years, the concept of a multi-user CO_2 transportation infrastructure in the Rotterdam harbour, transporting CO_2 to offshore gas fields has received attention (Ros, 2014).

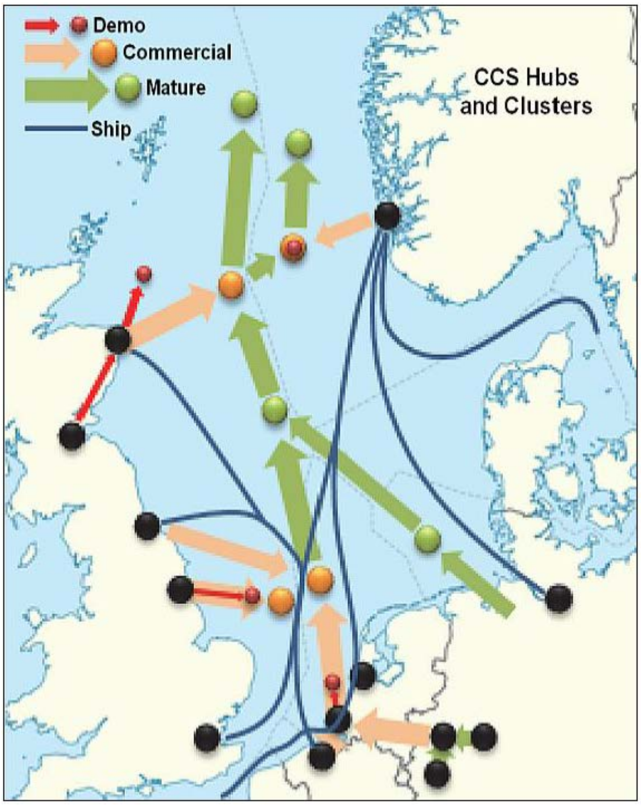

Figure 1: Map of the North Sea region with indicative CO_2 flows (yellow and green arrows) from industrial clusters (black dots) to offshore storage locations / clusters (orange and green dots). Blue curves indicate potential ship transport routes, linking industrial clusters to inlets (hubs) to offshore pipelines. Figure reproduced from NSBTF (2017).

e) Description of the project and its objectives

The Rotterdam Nucleus Project will provide the foundations for a high-volume CO_2 transportation infrastructure system from mainland Europe to CO_2 storage locations in the Dutch and UK sections of the North Sea. The infrastructure is designed to be over-sized, capable of providing CO_2 transport capacity for pre-commercial and commercial phase CCS deployment in Rotterdam, as well as possible future links to industrial areas of third-party countries. The initial users of the Rotterdam Nucleus is planned to be the ROAD CCS Project located in the Maasvlakte area of the Rotterdam harbour, and also gas producers in the North sea exploiting gas fields with a high CO_2 content. The Rotterdam Nucleus is also intended to be able to provide a service for possible future CO_2 flows from the Port of Antwerp and the Ruhr area of

Germany. The Rotterdam Nucleus has a physical link with the UK, but can also have a significant impact on the speed of CCS deployment in other neighbouring countries, as the foundations for high-capacity CO_2 transport and storage in the North Sea will be realised.

Rotterdam is a highly suitable location for a CO_2 transportation gateway, given both its proximity to large industrial clusters, such as Antwerp, the Rhine-Ruhr region, and Rotterdam itself, and considerable CO_2 storage sites in pressure depleted natural gas fields and potentially saline aquifers in the Southern North Sea. Within a radial distance 200km, there are CO_2 emission sources stemming from the power and industrial sectors of Rotterdam, Antwerp and North Rhine-Westphalia accumulating to approximately 260 $MtCO_2$/a.

The Rotterdam Nucleus PCI proposal is unique in the sense that in addition to providing CO_2 transport services to onshore energy and industrial emitters, it also allows transportation from offshore sources of CO_2, CO_2 from high CO_2 content gas fields in the UK and Dutch parts of the Southern North Sea, to geological storage sites. A number of significant North Sea gas discoveries are currently uneconomical to produce due to high CO_2 content of the contained gas. Two specific fields are identified within the project, namely Earlham (“Fizzy”) on the UK side, and P01-FA on the Netherlands side. Together, these closely located fields combined have reserves of 12 bcm of natural gas (TNO 2007, Swift Exploration Ltd, 2017). CO_2 capture technology can allow the CO_2 to be stripped from the field gas offshore, ready to be compressed, transported and stored. More details are provided at B1.b (Section 3.1).

The objectives of the Rotterdam Nucleus Project are therefore:

- Provide large scale CO_2 transportation for emitters in the Port of Rotterdam to 40 Mt of well-defined CO_2 storage capacity within 20km of the Dutch coast, and to several hundreds of megatonnes of storage further offshore.
- Over-size pipelines, compression and utility equipment to allow future use by third-party countries[4] based on priority CO_2 transport corridors identified by Member State governments through the North Sea Basin Task Force.
- Contribute to EU energy security by unlocking stranded natural gas reserves in both the UK and the Netherland’s sectors of the North Sea, and use a portion of the value to contribute to the costs of a 130km CO_2 trunkline passing across or close to future CO_2 storage sites with a potential storage capacity of 150 $MtCO_2$.

This dual-purpose function of the infrastructure represents an important value proposition that can lower the overall implementation costs of the infrastructure. Unlocking the value from stranded[5] natural gas reserves can support energy security in the EU, help lower the costs of CCS deployment, and in-turn facilitate low-carbon industrial development in key industrial clusters. The Rotterdam Nucleus project has also been designed, taking into account the TEN-E 347/2013 regulations, specifically to address the necessity for PCI’s to be able to

---

[4] Not currently affiliated with this PCI application

[5] The term ‘stranded’ is used as these fields are uneconomical to produce due to the high CO_2 content of the field gas.

This project is funded by the European Union

demonstrate clear financial and societal benefits, the former being highly challenging given current climate policy incentives.

The Rotterdam Nucleus project is comprised of three pipeline components, the development of which is co-dependent. It is envisaged that these three pipeline components would be developed simultaneously with a planned operation start date of between 2022 and 2024. An overview of the pipeline route, potential CO_2 sources and sinks is provided in Figure 2.

Table 1: Overview of compliance of the Rotterdam Nucleus to the general criteria of the TEN-E regulation

General criteria according to Article 4(1) of TEN-E regulation	Overview of compliance
a) The project is necessary for at least one of the energy infrastructure priority corridors and areas	This project is necessary for the Priority Thematic Area - Cross-border carbon dioxide network: development of carbon dioxide transport infrastructure between Member States and with neighbouring third countries in view of the deployment of carbon dioxide capture and storage
b) The potential overall benefits of the project, assessed according to the respective specific criteria (as defined in the next section) outweigh its costs, including in the longer term	Without CEF financing the Rotterdam Nucleus does not lead to a positive business case, with a base case NPV of -€56.3 million. With a 50% capital grant from the CEF the Rotterdam Nucleus could achieve a NPV of €41.5. Including a social cost of €60/tCO_2 transported, the project results in an IRR of 174%.
c) The project meets any of the following criteria: i) Involves at least two Member States by directly crossing the border of two or more Member States; ii) Is located on the territory of one Member State and has a significant cross-border impact; iii) Crosses the border of at least one Member State and an EEA country.	The Rotterdam Nucleus PCI involves the Netherlands and the United Kingdom, with a CO_2 pipeline directly crossing the border of these Member States. The Rotterdam Nucleus may have significant cross-border impact for third-party member states through the provision of CO_2 transportation capacity. The infrastructure is capable of transporting CO_2 amounts exceeding the local amounts expected to be captured.

This project is funded by the European Union

Table 2: Overview of compliance of the Rotterdam Nucleus to the specific criteria for CO2 transport infrastructure of the TEN-E regulation

Specific criteria for CO_2 transport infrastructure project under TEN-E Annex II.4	Corresponding benefits	Overview of compliance
Avoidance of CO_2 emissions while maintaining security of energy supply	Reduction of carbon damages	The Rotterdam Nucleus project has the potential to transport 114 $MtCO_2$ cumulatively over the 20 year assessment period. The cumulative net reduction is 112 $MtCO_2$. The social cost benefit analysis results in a monetary reduction in carbon damages totalling €6.84 billion (undiscounted).
	Security of energy supply and diversification of energy resources	The project supports security of supply by enabling a maintained diversification of power supply while reducing the climate impact of doing so. The project also enables large quantities of natural gas to be extracted from the North Sea while preventing the co-produced CO_2 from entering the atmosphere.
Increasing the resilience and security of CO_2 transport	Contribution to the development of knowledge with respect to CO_2 transport	This project connects the first onshore capture cluster to the first offshore storage cluster. There are no other planned CCS projects in Europe at this time. There is no location where transport could be performed at a lower cost (large volumes of CO_2 with short distance to storage locations).
The efficient use of resources, by enabling the connection of multiple CO_2 sources and storage sites via common infrastructure and	Future potential to connect multiple CO_2 sources and storage sites via the proposed infrastructure	In Rotterdam, there are 10 CO_2 point sources with annual emissions of >0.5 $MtCO_2/a$, totalling 23 $MtCO_2/a$ within 25 km of the Rotterdam CO_2 Gateway. In Antwerp, 80 km from Rotterdam, there are 9 CO_2 point sources with annual emissions of >0.5 $MtCO_2/a$, totaling

This project is funded by the European Union

Specific criteria for CO_2 transport infrastructure project under TEN-E Annex II.4	Corresponding benefits	Overview of compliance
minimising environmental burden and risks		13 $MtCO_2/a$. In the North Rhine Westphalia region of Germany, emission sources in the region have combined CO_2 emissions of 160 $MtCO_2/a$. This region is approximately 200 km from the Rotterdam CO_2 Gateway. The main spine pipeline is deliberately over-sized to create future expansion potential to increased diversity of sources and storage locations in the Southern North Sea and potential links to the UK.
	Extension of the economic or regulatory lifetime of existing assets	The reuse of existing offshore natural gas production assets for CO_2 storage as part of the Rotterdam Nucleus project, can result in an economic saving of €85 million, compared to the installation of new infrastructure.

1) **Rotterdam collection network link:** (18 km), A low-pressure pipeline connect to the existing OCAP CO_2 transport pipeline to the ROAD CCS Project. This pipeline enables the transportation of excess CO_2 during the winter months from the OCAP system, prior to transportation through the Rotterdam CO_2 Gateway (see below). This pipeline can later be used for CO_2 transport of future capture sources and has a maximum capacity of 4 $MtCO_2/a$ at 22 bar, but can be operated at a higher pressure (44 bar) increasing the capacity to 11 $MtCO_2/a$.

2) **The Rotterdam CO_2 Gateway:** A 25 km high pressure CO_2 pipeline with a capacity of 10 $MtCO_2/a$ linking the ROAD CCS Project to the P18-A platform, with associated onshore compression equipment. The pipeline is intended to transport CO_2 initially from the ROAD CCS Project, and for future CO_2 sources in the Port of Rotterdam.

3) **The Dutch North Sea Trunkline:** A main spine pipeline of around 130km will extend from the Earlham “Fizzy” and P1-FA fields in the Southern North Sea to the P18 storage facility. The spine pipeline is designed to be oversized for the initial use, which is to transport the separated CO_2 from these high-CO_2 fields to the initial storage locations of P18 / P15. The route of the pipeline will be planned to pass over potential future CO_2 storage sites in the Dutch P15 and Q1 blocks, for example, perhaps with T-junctions on platforms at interstitial locations allowing future expansion once storage sites are needed and sufficiently characterized. Alternatively the route to P18 could pass directly over the Q1 or P15 infrastructure. The pipeline would have a capacity of 10 $MtCO_2$/a. The initial flow, for the first 10 years of the project, will be from the North Sea gas fields to the P18 storage facility. Subsequently, the trunkline would be reversible and used to transport CO_2 from commercial scale projects in Rotterdam, via the Rotterdam CO_2 Gateway, and beyond to the connected offshore storage sites. The Rotterdam CO_2 Gateway could be used to transport CO_2 from initial CCS projects in Rotterdam to the P18 block from 2023 (technically as early as 2021). Figure 4 and Table 4 provide more information on the initial prospective storage sites to be accessed through the Rotterdam CO_2 Gateway and the Dutch North Sea Trunkline.

Table 3: Overview of key specifications for pipeline segments of the Rotterdam Nucleus

Pipeline segment	Length (km)	Diameter (mm)	Capacity (Mt/a)	Operating pressure
Rotterdam collection network link	18	600	4	Low (22 bar)
			11	Low (44 bar)
The Rotterdam CO_2 Gateway	25	610	10	High
The Dutch North Sea Trunkline	130	610	10	High

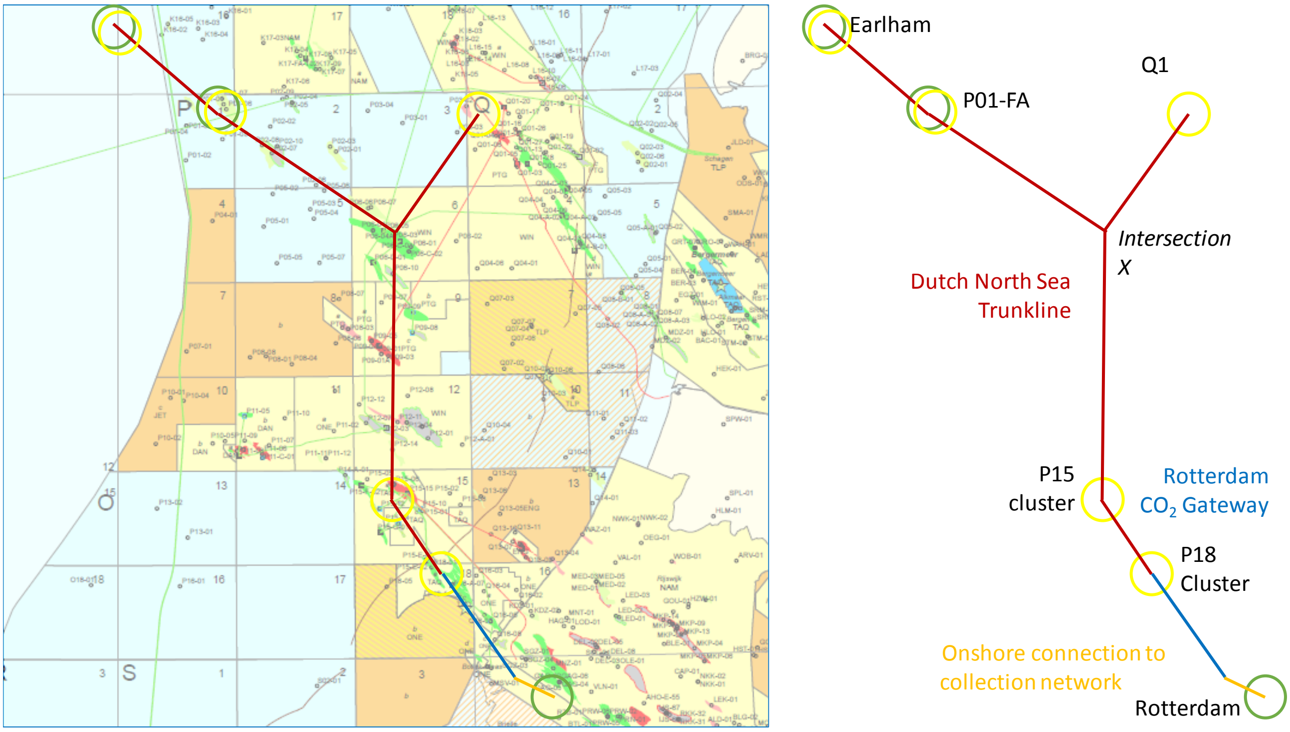

Figure 2: Left: A simplified outline of the PCI structure overlain on a map of Dutch offshore. Right: the PCI structure repeated for clarity of the PCI elements. Green circles represent CO_2 sources, yellow circles indicate CO_2 storage locations. The offshore gas fields Earlham and P01-FA first deliver CO_2, from separation from the produced gas, and become CO_2 stores after the end of gas production. The pipeline structure is divided into three segments: an onshore section to connect to the Rotterdam collection network (orange), the offshore Rotterdam CO_2 Gateway (blue) and the offshore Dutch North Sea Trunkline (red).

f) Extent of physical presence of infrastructure in each of the involved countries

1. *Rotterdam collection network link*

   Netherlands: An 18 km onshore pipeline following an existing pipeline corridor through the eastern section of the Port of Rotterdam. The pipeline starts at 51°55'29.2"N 4°10'53.2"E and ends at 51°57'47.6"N 4°01'21.2"E.

   United Kingdom: None.

2. *The Rotterdam CO_2 Gateway*

   Netherlands: 5 km of 610 mm diameter steel pipeline leading North from the ROAD CCS Project MPP3 at 51°57'47.6"N 4°01'21.2"E, following an existing pipeline corridor to the coast at 51°58'47.5"N 4°02'48.8"E. At the coast a compressor station will be installed. A 20km 610 mm diameter steel pipeline will be installed from the compressor station on the coast to the riser of the P18-A platform, at 52°06'50.6"N 3°58'02.1"E. Other pipeline related infrastructure will include any equipment related to metering, monitoring, inspection, horizontal drilling, pipe laying, rock dumping, permitting, riser and tie in.

United Kingdom: None.

3. *The Dutch North Sea Trunkline*

Netherlands: 90km of 610 mm diameter steel pipeline from P18-A to a platform riser P01-FA at 03°18’E, 52°58’N and on to the North Sea shared borderline. P01-FA development will include gas recovery, processing and membrane separation facilities; also the main pipeline conditioning facilities involving compression and drying.

United Kingdom: 12km of 610mm diameter steel pipeline from the North Sea shared borderline leading to the Earlham field at 02°50’E, 53°03’N. The Earlham field development will include gas recovery, processing and membrane separation facilities and gas evacuation infrastructure.

g) Implementation status

The Rotterdam Nucleus is currently in concept phase, however a number of components of the project are at advanced planning stages since they have been or are now the subject of CCS demonstration or research activities in past or present projects. An overview per project element is provided below:

Rotterdam collection network link

This section of the PCI is currently in concept phase only; Ros et al. (2014) describe possible concepts for this pipeline.

Rotterdam CO_2 Gateway pipeline

As part of the ROAD CCS Project, a European funded CCS project currently at FID stage (planned end-2017), a FEED study for a pipeline linking the CO_2 capture unit in the Maasvlakte to the P18-A platform (with wells drilled to potential CO_2 storage sites in the P18 block of the Dutch north sea) was completed in 2011/2012. The FEED was based on a pipeline specified as having a diameter of 16 inches (40.6 cm), a total length of 25km (5km onshore, 20km offshore), and an operating pressure of 175 bar. The maximum capacity of the pipeline in the FEED study was 5 $MtCO_2$/a, which is half of the capacity proposed for the Rotterdam CO_2 Gateway pipeline. Therefore the FEED study would need to be adjusted for the larger diameter pipeline as proposed in this application.

The original pipeline FEED study is not publicly available, but would be made available for the Rotterdam Nucleus project should it proceed to the feasibility phase.

A 400-page Environmental Impact Assessment (EIA) for the pipeline was completed in accordance with Dutch law in 2011. This EIA is available for download here. The route of the pipeline and spatial planning requirements for the Rotterdam CO_2 Gateway is expected to be the same as the lower capacity pipeline. Therefore the previously completed work in the

This project is funded by the European Union

FEED study and in the EIA, albeit for a pipeline with an different specification, will undoubtedly contribute to speed and economic efficiency of planning the Rotterdam CO_2 Gateway.

The Dutch North Sea Trunkline

This section of the PCI is currently in concept phase only.

Initial CO_2 sources

Details on current implementation status of the initial potential CO_2 capture locations are provided below:

ROAD

The ROAD Project is a planned post-combustion capture unit on a coal-fired power plant in the Rotterdam harbour, capable of capturing 1.1 MtCO_2 per annum (equivalent of decarbonizing 250 MWe coal-fired power production). In September 2009, the ROAD CCS Project was granted financial support from the European Commission under the European Energy Programme for Recovery (EEPR). In May 2010, the project was also granted additional national support from the Dutch government. The final Environmental Impact Assessment and permit applications were submitted in June 2011. The FEED study for the project was also completed in 2011. The storage license for the P18-4 field was awarded to TAQA and made irrevocable in 2013. Due to economic difficulties the project has been severely delayed, but is expected to take a final investment decision (FID) in 2017. Should this be the case the project could be operation by 2021.

OCAP

The Rotterdam Nucleus has an onshore section that extends from the existing OCAP pipeline, to the ROAD CCS Project, the start of the Rotterdam CO_2 Gateway, thereby connecting the Rotterdam collection network with the offshore transport network. The OCAP system delivers CO_2 to greenhouses, but has excess CO_2 available for storage during the winter months; this is about 0.5 MtCO_2/a.

P1-FA gas field

The P01-FA gas field was discovered in 1977 with exploration well P01-01. Subsequently the field was appraised with the wells P01-06 and P01-07. The gas is contained in the sandstone reservoir of the Upper Slochteren Member (ROSLU), in a carbonate reservoir of the Zechstein Group (ZEZ3C) and also in the Triassic Solling Sandstone reservoir. The field has not been developed and currently lies in the P01 exploration area. Despite considerable gas reserves of 12 bcm in the Upper Slochteren reservoir, the field gas is composed of high levels of CO_2 at 32%, which means since its discovery it has been uneconomical to produce (TNO, 2017). However, if the CO_2 can be separated from the CH_4 on a platform for example, and the CO_2 transported and stored, considerable value could be unlocked from the field. Based on the known gas composition of the P1-FA gas field, the field would produce 11.7 MtCO_2 should the gas field be exploited.

Earlham gas field (formerly 'Fizzy')

This project is funded by the European Union

The Earlham gas discovery is located in block 50/26 on the UK continental shelf, within 8km of the UK/Dutch border. Despite the considerable potential gas reserves held in the discovery, estimated at 3.7 bcm, a license for the field was relinquished in 2007 because of the high CO_2 content (50%) of the field gas. Since 2014 Swift Exploration has held an exploration license for the Earlham field and is evaluating economic and environmentally responsible options for exploiting the fields. Similar to the P1-FA field described above, carbon capture and storage is necessary to unlock the value of the natural gas in this field. Based on the known gas composition of the Earlham discovery, the field would produce 14.1 $MtCO_2$ should the gas field be exploited.

CO_2 storage locations

CO_2 storage locations have been identified to be suitable for the permanent geological storage of 280 Mt of CO_2, far greater than the initial requirements for the first 20 years of the Rotterdam Nucleus PCI. The CO_2 storage locations are in different stages of availability, for example with regards to permitting and site characterisation. An overview is provided in the list below:

- P18-4 gas field: CO_2 storage permit in place (8 $MtCO_2$ capacity available).
- P18-2 gas field: Risk assessment conducted. Requires further assessment and permit application (32 $MtCO_2$ potential capacity).
- P15 complex: Three further depleted gas fields, requiring risk assessments and permit application (34 $MtCO_2$ potential capacity).
- Q1 saline formation: Large saline aquifer with considerable data availability. Further site characterisation, risk assessment and permit application necessary (110 $MtCO_2$ potential capacity).
- The Earlham and P01-FA fields will be available for CO_2 storage once the fields are depleted. That is expected to occur around 2040, but is likely to shift.

The approximate locations of the potential CO_2 storage sites can be found in Figure 3.

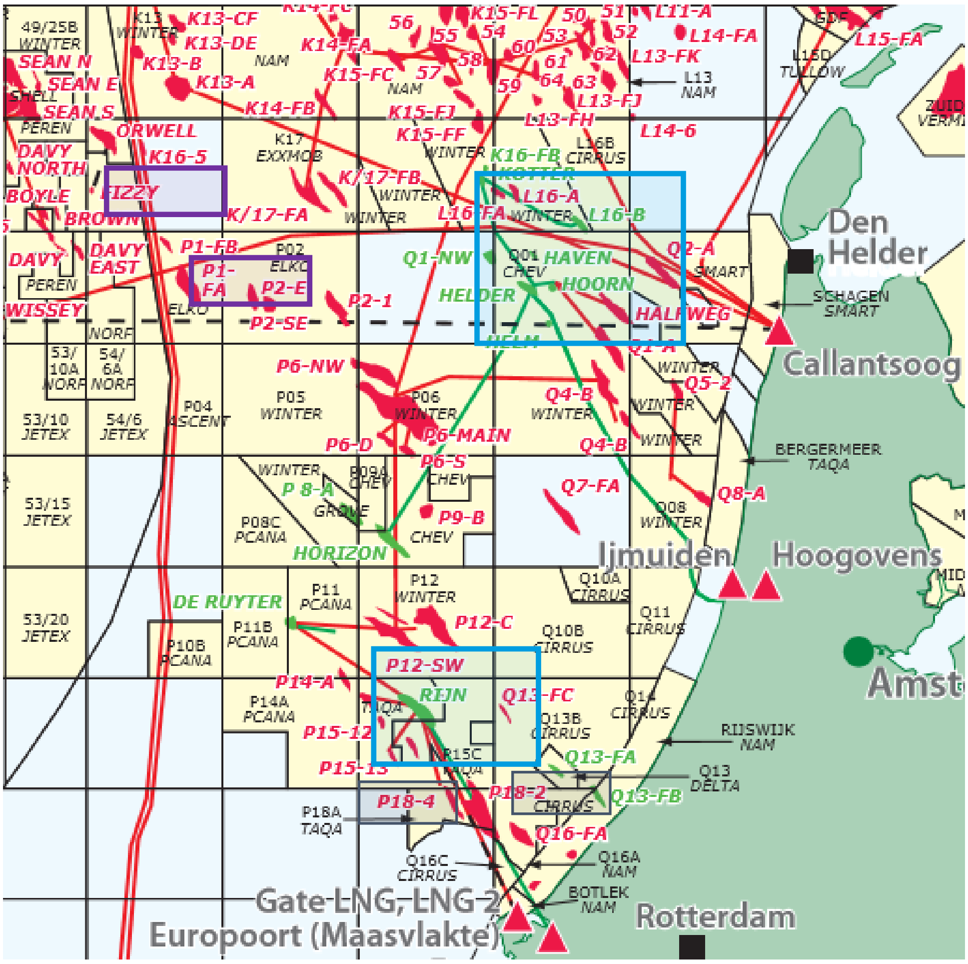

Figure 3: Approximate Locations of potential CO_2 storage sites in the Dutch North Sea P18-4, P18-2, P15 complex and Q1 saline aquifer (blue outline), and the CO_2 rich gas discoveries ‘Fizzy’ (Earlham – UK) and P1-FA (Dutch) (purple outline) (Offshore Magazine, 2013).

P18-4 gas field

The P18-4 field is a near-depleted gas field at a depth of 3.5 km under the seabed, located approximately 20 km off the Dutch coast in the North Sea. P18-4 is one of a number of gas fields in the P18 and P15 licensing blocks on the Dutch continental shelf of which TAQA Offshore B.V. holds the production licenses. The gas production has reduced the field pressure from 340 bar to 20 bar, and the field has since been identified as a highly suitable CO_2 storage formation, with an approximate capacity of 8 $MtCO_2$. The P18-4 field is produced through the P18-4A2 well, connected to the P18-A platform. The P18-4 field continues to produce a small amount of natural gas.

TAQA received an irrevocable CO_2 storage permit under the EU Directive on the geological storage of CO_2 (2009/31/EC) for P18-4 in September 2013. To achieve this, the operators have complied with spatial planning, environmental impact assessments, public participation requirements and the Dutch mining law. Therefore the field has all relevant permits in place to initiate CO_2 injection, should the relevant CO_2 infrastructure be developed.

P18-2 gas field

This project is funded by the European Union

The P18-2 gas field is the largest field in the P18 block, located near the P18-4 field. The P18-2 gas field is also connected to the P18-A platform. The gas field has been producing since 1992, and the original amount of gas in place is estimated at 13.4 bcm. The gas field is expected to cease production in 2018. As part of the EIA of the ROAD project conducted in 2011, an initial risk assessment for CO_2 storage in the P18-2 field has been completed. The field is expected to have much the same geological characteristics as P18-4, and therefore be very suitable for CO_2 storage. Prior to any storage permit application, the condition of a number of suspended and abandoned wells needs to be re-assessed. Based on the amount of gas originally in place, the fields has a theoretical CO_2 storage capacity of 32 $MtCO_2$.

P15 Complex

The P15 complex is a cluster of gas fields together with the Rijn oil field located approximately 20km north-west from the P18 fields. The gas fields are connected to the P15-D platform, where the gas is processed to sales specification and exported through a 40 km 26” pipeline to the Maasvlakte, near Rotterdam. A number of gas fields, specifically the P15-9, P15-11 and P15-13 are expended but are highly suitable for CO_2 storage. An approximate total CO_2 storage capacity of 34 $MtCO_2$ is theoretically available. An initial storage assessment of the above fields concluded that the containment characteristics of the field are good and that risks for CO_2 storage are minimal (Neele, et al., 2011). The depleted gas fields of the P15 complex are considered as logical follow-on storage sites after P18-4 and P18-2.

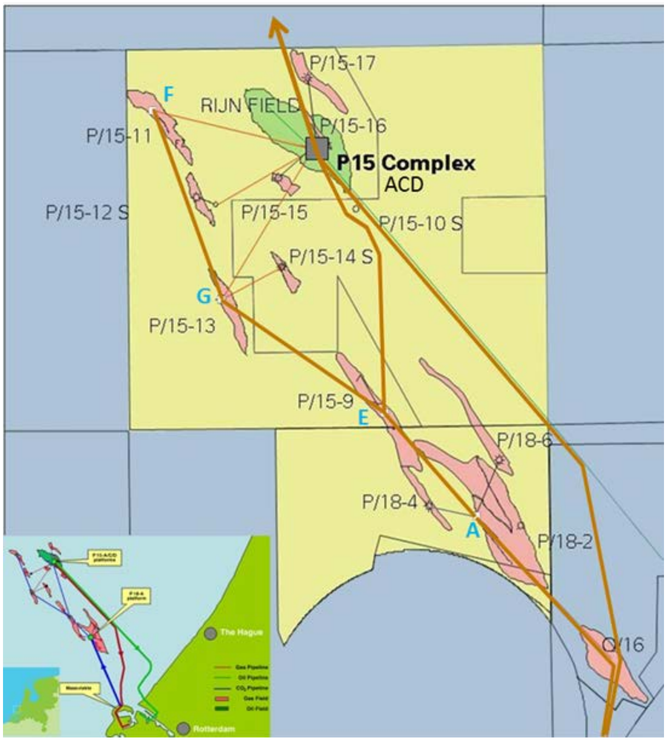

Figure 4: Locations of the gas fields located in the P18 and P15 blocks (courtesy of TAQA Energy B.V.). Table 4 gives the storage capacity of the gas fields (shown as red outlines); the platforms mentioned in Table 4 are indicated by blue capitals. The green outline under the P15-ACD platform is the Rijn oil field, a potential candidate for CO_2 enhanced oil recovery.

Table 4: Estimated CO_2 storage capacities (courtesy of TAQA Energy B.V. for data on gas reservoirs in the P18 and P15 blocks).

Reservoir / Platform	Reservoir p (bar)		CO_2 capacity	Fill order
	Initial	End 2016	Million tonnes	
P18-4 / P18-A	340	20	8	1
P18-2 / P18-A	355	25	32	2
P15-9 / P15-E	347	20	10	3
P15-13 / P15-G	288	35	8	4
P15-11 / P15-F	283	15	16	5
Earlham			25	7/8
P01-FA			35	7/8
Q1 structure			100	6

Q1 saline formation

The saline formation in the Q1 block that contains the Q1 oil fields could become the prime storage location for CO_2 captured in the Amsterdam and Rotterdam regions. The oil fields in the Q1 block, located at about 100 km from the Rotterdam coast, are close to the end of production, producing both water and oil. Water has been injected to optimize production from the fields. The water has been drawn from the saline formation in the crests of which are located the oil fields. As a result of these production activities, the pressure in the saline formation is now well below the hydrostatic (original) pressure. The voidage created by the production of water and oil can be used for CO_2 storage. A preliminary estimate of the storage capacity of the saline formation is in the order of 100 Mt CO_2 (Neele, et al., 2011). Continuing production of saline formation water is also an option, which could further increase the field's storage potential significantly. In addition to the significant storage capacity, the saline formation can potentially accommodate high to very high injection rates (several megatonnes per well per year).

A confidential prefeasibility study of CO_2 storage in the Q1 saline formation has been completed by TNO in 2011. However considerable site characterisation work must still be completed before this site could be readied for utilisation as a CO_2 storage site.

h) Start and end date of construction phase

The start date for construction of the onshore connection to the collection network, the Rotterdam CO_2 Gateway and the Dutch North Sea Trunkline is notionally planned for 2020, with all three sections expected to be completed by 2022.

i) Anticipated start of operation

The anticipated start date of operation for the three sections of the Rotterdam Nucleus PCI is between 2022 and 2024, although technically the P18-4 field is ready for conversion today.

j) Anticipated project lifetime

The anticipated project lifetime of the Rotterdam Nucleus is approximately 40 years. For sections B.3 ‘Cost benefit analysis’, a tenure of 20 years is assumed as per the accompanying guidance document.

This project is funded by the European Union

3 PART B: TECHNICAL AND FINANCIAL INFORMATION

3.1 B.1 detailed project information

a) Project location

The Rotterdam Nucleus is comprised of three sections of CO_2 transportation pipeline, the onshore connection to the Rotterdam collection network, the Rotterdam CO_2 Gateway and the Dutch North Sea Trunkline.

The start location of the Rotterdam collection network link is at an end point of the OCAP CO_2 pipeline at 51°55'29.2"N 4°10'53.2"E in the Rozenburg area of the harbour. The end location is the start location of the Rotterdam CO_2 Gateway.

The start location of the Rotterdam CO_2 Gateway is the ROAD CCS Project, at the Uniper MPP3 coal-fired power plant in the Maasvlakte area of the Port of Rotterdam (51°57'47.6"N 4°01'21.2"E). This section of the pipeline ends at the platform riser of the P18-A platform approximately 20km from the Dutch coast at 52°06'50.6"N 3°58'02.1"E.

The start location of the Dutch North Sea Trunkline is at the P18-A platform at 52°06'50.6"N 3°58'02.1"E. The Trunkline will follow a route, yet to be fully determined, passing potential future CO_2 storage locations in the Dutch North Sea. The Trunkline will end at, a to be built, offshore platform in the vicinity of the Earlham gas prospect on the UK continental shelf close to 02^{o}50’E, 53^{o}03’N.

b) Location and capacity of capture plant(s)

Table 6 shows the location and capacity of the capture plants included in the current CO_2 supply scenario. CO_2 from the Earlham and P01-FA fields is from gas processing at the platforms. The ROAD project plans to produce at a rate of 1.1 Mt/a. The OCAP collection system currently has excess CO_2 during winter of a total of 0.5 Mt/a. Two additional source in the Rotterdam harbour area are expected to start producing CO_2 and connect to the PCI structure by 2025.

The **future sources** are potential high-purity CO_2 sources within close proximity to the Rotterdam collection network which, given an increase in the cost of emitting CO_2 under the EU ETS, could become users of the Rotterdam Nucleus project by 2025. These sources wish to remain anonymous for the purposes of this PCI application. Figure 13 contains a simple marginal abatement cost curve for the key CO_2 sources in the Rotterdam habour area. Based on a simple assumption that all emitters with a CO_2 capture price of less than the prevailing EU ETS price would abate their emissions, with an assumed ET ETS price projection of €25/tCO_2 by 2025, approximately 3.5 MtCO_2 could be captured and sent for storage through the Rotterdam Nucleus. Based on this, conservative estimates have been made of CO_2 flows from two sources.

Table 5: Location and capacity of the CO_2 capture plants.

Capture Plant	Location	Max CO_2 flow	Total Capacity CO_2
Earlham (A)	UK SNS 02°50’E, 53°03’N	3.1 Mt/a	14.1 Mt
P01-FA (B)	Netherlands SNS 03°18’E, 52°58’N	1.1 Mt/a	11.7 Mt
ROAD CCS Project (C)	Maasvlakte, Rotterdam 51°57'47.6"N 4°01'21.2"E	1.1 Mt/a	22 Mt
CO_2 flow from OCAP	OCAP pipeline at 51°55'29.2"N 4°10'53.2"E	0.5 Mt/a	0.5 Mt/a for 20 years, 10 Mt total; flow can continue after 20 years
Future source Rotterdam 1	Hypothetical source	1.5 Mt/a	Flow expected to start 2025
Future source Rotterdam 2	Hypothetical source	1.6 Mt/a	Flow expected to start 2025

c) Location and capacity of liquefaction facility and buffer storage

No liquefaction or buffer storage facilities are planned in the initial phase of the Rotterdam Nucleus.

d) Location and capacity of agreed CO_2 transport destination(s) (storage, usage)

The CO_2 transported will be initially stored in the P18-4 depleted pressure gas reservoir via the P18-A platform location at 52°06'50.6"N 3°58'02.1"E.

e) Volume of CO2 transported to point of storage (as applicable)

Table 7 shows the CO_2 volumes that are produced at the different capture plants, throughout the 20-year period considered in the cost benefit analysis. All CO_2 that is produced is transported and stored. See below, under B.1.l for the flow through the individual PCI segments.

Table 6: CO_2 volumes produced and transported.

CO2 Mt/a				Sources		
Year	Earlham	P1-FA	Road CCS Project	CO_2 from OCAP	Future source Rotterdam 1	Future source Rotterdam 2
2021	0.0	0.0	0.0			
2022	0.0	0.0	0.0			
2023	1.0	1.1	1.1	0.5		

CO2 Mt/a				Sources		
2024	3.1	1.1	1.1	0.5		
2025	3.0	1.1	1.1	0.5	1.5	1.6
2026	1.7	1.1	1.1	0.5	1.5	1.6
2027	1.2	1.1	1.1	0.5	1.5	1.6
2028	0.9	1.0	1.1	0.5	1.5	1.6
2029	0.7	0.9	1.1	0.5	1.5	1.6
2030	0.6	0.8	1.1	0.5	1.5	1.6
3031	0.5	0.7	1.1	0.5	1.5	1.6
2032	0.4	0.6	1.1	0.5	1.5	1.6
2033	0.3	0.6	1.1	0.5	1.5	1.6
2034	0.3	0.5	1.1	0.5	1.5	1.6
2035	0.2	0.5	1.1	0.5	1.5	1.6
2036	0.2	0.4	1.1	0.5	1.5	1.6
2037	0.1	0.4	1.1	0.5	1.5	1.6
2038	0.1	0.3	1.1	0.5	1.5	1.6
2039	0.0	0.0	1.1	0.5	1.5	1.6
2040	0.0	0.0	1.1	0.5	1.5	1.6
2041	0.0	0.0	1.1	0.5	1.5	1.6
2042	0.0	0.0	1.1	0.5	1.5	1.6

f) Volume of CO_2 transported to point of usage (as applicable)

Not applicable at this stage of the Rotterdam Nucleus.

g) Initial off-take agreement in place

There are currently no formal off-take agreements, however a number of potential users of the infrastructure are included as ‘affiliated applicants’.

h) Physical characteristics of the transport infrastructure

Rotterdam collection network link

This is an onshore pipeline following an existing pipeline corridor through the eastern section of the port. This section of pipeline is 18 km, DN600 (24 inch), and a capacity of 4 $MtCO_2$/a when operating at the initial proposed pressure of 22 bar. The pipeline will be designed to be able to operate at higher pressures up to 44 bar, whereby the capacity will increase to 11 $MtCO_2$/a. The approximate route of the Rotterdam collection network link is provided in Figure 5.

This project is funded by the European Union

Figure 5: Route of the proposed Rotterdam collection network link (blue) and the existing OCAP CO_2 collection system (green)

Pipeline from Rotterdam to P18-A (Rotterdam CO_2 Gateway)

This is an offshore pipeline that connects the onshore compression facility at the Q16-Maas site (at the western edge of the Maasvlakte) with the offshore P18-A platform. The pipeline traverses the harbour entrance (constructed through directional drilling) and a busy shipping lane.

Pipeline connections between P18-A, P15-E, P15-G and P15-F

Figure 4 shows the locations of the platforms that provide access to the different gas fields. The logical order of storing in the fields is given in Table 4. The platforms in the P18 and P15 clusters are relatively closely spaced; the optimum, or most cost effective way of connecting the platforms to develop each depleted field storing CO_2 from both Rotterdam and Earlham / P01-FA remains to be defined. Detailed study of the individual fields will establish the storage capacity and injection rates, which will define the timing of the start of injection in each field. This will also be the necessary input for the design of the intra-platform network, as well as the location of the connection to the North Sea Trunkline.

Another key boundary condition is the availability of space and load capacity of the different platforms, which defines where transport facilities can be located. The design of the intra-platform network and connection to the Trunkline will be part of a PCI study.

Pipeline P18/P15 to P01-FA and Earlham

This is a fully off-shore section of the PCI pipeline with a uniform diameter of 610mm, concrete covered and following established pipeline routes wherever possible. Overall length is 100 km with a subsea Tee at P01-FA to a suitable manifold platform and a platform manifold at Earlham. An additional subsea branching Tee will be fitted at around 47 km to allow for a low-cost subsequent connection to large capacity potential aquifer storage in the Netherlands Q1 quadrant. If tees are not a technical optimum solution then an up-and-over solution using existing platforms along the route will be employed which may give access to further storage capacity.

The pipeline will be designed to operate reversibly in the dense phase of CO_2 with a maximum pressure of around 210 bar and a design throughput of 10Mt/a (max 13Mt/a).

Figure 2 shows a map of the indicative location and route of this pipeline. The optimal routing is to be established in a feasibility study, in which key parameters will include the timing of development of the Q1 store and the likelihood of development of other stores.

i) Timeline of construction activities (planning overview)

Table 7: Timeline of construction activities

Period	Development activities
PCI Period April 2017 – April 2019	**Not accepted** on PCI list – stop process; consider future application in subsequent round
	Accepted on PCI list **Activities as part of the PCI** *General* • Explore funding routes for (pre) feasibility/FEED studies • Identify possible national funding sources i.e. TKI financing for feasibility work • Market test industry involvement and potential financial contributions for feasibility work (NL/UK) • Be prepared for ROAD to take FID and reach agreement with Q16 Maas for storage and/or P18-4 *Onshore connection to Rotterdam collection network* • Feasibility and FEED • Evaluate CO_2 source potential along the route and seek interest to join project and invest in CO_2 capture. *Rotterdam CO_2 Gateway* • Apply for CEF financing for update of existing FEED • Conduct FEED study

This project is funded by the European Union

Period	Development activities
	Dutch North Sea Trunkline • Pre-feasibility work • Prepare application for CEF financing for FEED study **Activities in parallel to, but not as part of the PCI** • Contingent on FEED of the Rotterdam CO_2 Gateway, progress with Maas Q16 ROAD FID • Conduct storage site appraisal and prepare storage permit application for the P18-2 field • Conduct storage site scoping of North sea storage assets in P15/Q1 using existing data (e.g., ERA-NET ACT, Horizon2020); the results are used for PCI routing and in the pre-feasibility study for the Dutch North Sea Trunkline. • Continue to try to get Ports of Rotterdam and Antwerp to join.
PCI Period April 2019 – April 2021	If sufficient support remains for the project, it can remain on the PCI list, then: **Activities as part of the PCI** *General* • Identify potential TSO to operate project offshore • Identify cost sharing structure between CEF funds, countries (UK/NL) and affiliated industrial entities *Onshore connection to Rotterdam collection network* • Apply for CEF financing for pipeline, start EPC early if possible *Rotterdam CO_2 Gateway* • Conduct or complete FEED study • Apply for CEF financing for pipeline, start EPC early if possible

Period	Development activities
	Dutch North Sea Trunkline • Apply for CEF financing for FEED study • Conduct FEED study **Activities in parallel to, but not as part of the PCI** • Apply for storage permit in P18-2 field and extension of permit for P18-4 field • Raise funding through public/private initiatives to Initiate detailed site characterization of reservoirs in North sea CO_2 storage prospects in P15/Q1, using new and existing data • Conduct storage site appraisal and prepare storage permit applications for the P15 fields, aquifer and/or EOR if screening is positive
PCI Period April 2021 – April 2023	If sufficient support remains for the project, it can remain on the PCI list, then: **Activities as part of the PCI** *General* • Transfer offshore project promoter applicant from Port of Rotterdam to TSO *Onshore connection to Rotterdam collection network* • Complete EPC *Rotterdam CO_2 Gateway* • Complete EPC *Dutch North Sea Trunkline* • Start EPC **Activities in parallel to, but not as part of the PCI**

Period	Development activities
	• Develop P18-4 and P18-2 field for CO_2 injection and storage • Apply for storage permits in P15 fields • Conduct storage site appraisal and prepare storage permit application for the Q1 structure
PCI Period April 2023 – April 2025	If sufficient support remains for the project, it can remain on the PCI list, then: **Activities as part of the PCI** *PCI constructed and ready to start operations* **Activities in parallel to, but not as part of the PCI** • Develop P15 fields for CO_2 injection and storage • Apply for storage permit for the Q1 structure

j) Schedule of operational and monitoring activities

The schedule of operation and monitoring activities will be developed during the feasibility phase of the Rotterdam Nucleus project.

k) Number, type and details of agreed proposed connections

Table 8: Number and locations of proposed connections

Connection	Location
Rotterdam collection network link	
Connection of Rotterdam collection network link to OCAP pipeline	51°55'29.2"N 4°10'53.2"E
Connection of Rotterdam collection network link to ROAD CCS Project	51°57'47.6"N 4°01'21.2"E
Rotterdam CO_2 Gateway	
Connection of Rotterdam CO_2 Gateway to the ROAD CCS Project	51°57'47.6"N 4°01'21.2"E
Connection of Rotterdam CO_2 Gateway to the P18-A platform	52°06'50.6"N 3°58'02.1"E
Dutch North Sea Trunkline	
Connection of the Dutch North Sea Trunkline to the P18-A platform	52°06'50.6"N 3°58'02.1"E
Connection of the Dutch North Sea Trunkline to the P1-FA field (platform not yet developed)	03°18’E, 52°58’N
Connection of the Dutch North Sea Trunkline to the Earlham gas field (platform not yet developed)	02°50’E, 53°03’N

The exact type of proposed connections are not yet known, and will be clarified during (pre-) feasibility work.

l) Proportion of transport capacity used by agreed proposed connections (%)

The usage of the Rotterdam Nucleus pipeline segments is shown in Figure 6, for the twenty-year period considered. The scenario of CO_2 supply results in a maximum usage of 40 – 45% for some segments, up to 75% for the onshore connection to the Rotterdam collection network. The negative usage shown in the figure represents flow reversal: around 2032 the P15-P18 fields reach their limit (storage rates, as well as total storage capacity) and the flow in the pipeline from these fields to the Q1 store reverses at the start of storage in the Q1 structure.

a) Demonstration of cross-border impact and future CO_2 transport network expansion potential

In Rotterdam, there are 10 CO_2 point sources with annual emissions of >0.5 $MtCO_2/a$, totalling 23 $MtCO_2/a$ within 25 km of the Rotterdam CO_2 Gateway. In Antwerp, 80 km from Rotterdam, there are 9 CO_2 point sources with annual emissions of >0.5 $MtCO_2/a$, totaling 13 $MtCO_2/a$. In the North Rhine Westphalia region of Germany, emission sources in the region have combined CO_2 emissions of 160 $MtCO_2/a$. This region is approximately 200 km from the Rotterdam CO_2 Gateway.

The Rotterdam Nucleus will generate the first elements of the North Sea CO_2 transport and storage infrastructure that will be necessary for the countries bordering the North Sea to use CCS as a key emission reduction measure. The plan set up by the NSBTF emphasizes the intention of the countries involved to use the storage potential under the North Sea (see Figure 1); the construction of the Rotterdam Nucleus will have a strong impact in all Member States involved.

Part C) of section B.2 provides further detail of potential future expansion the Rotterdam Nucleus to connect with sources and sinks of CO_2.

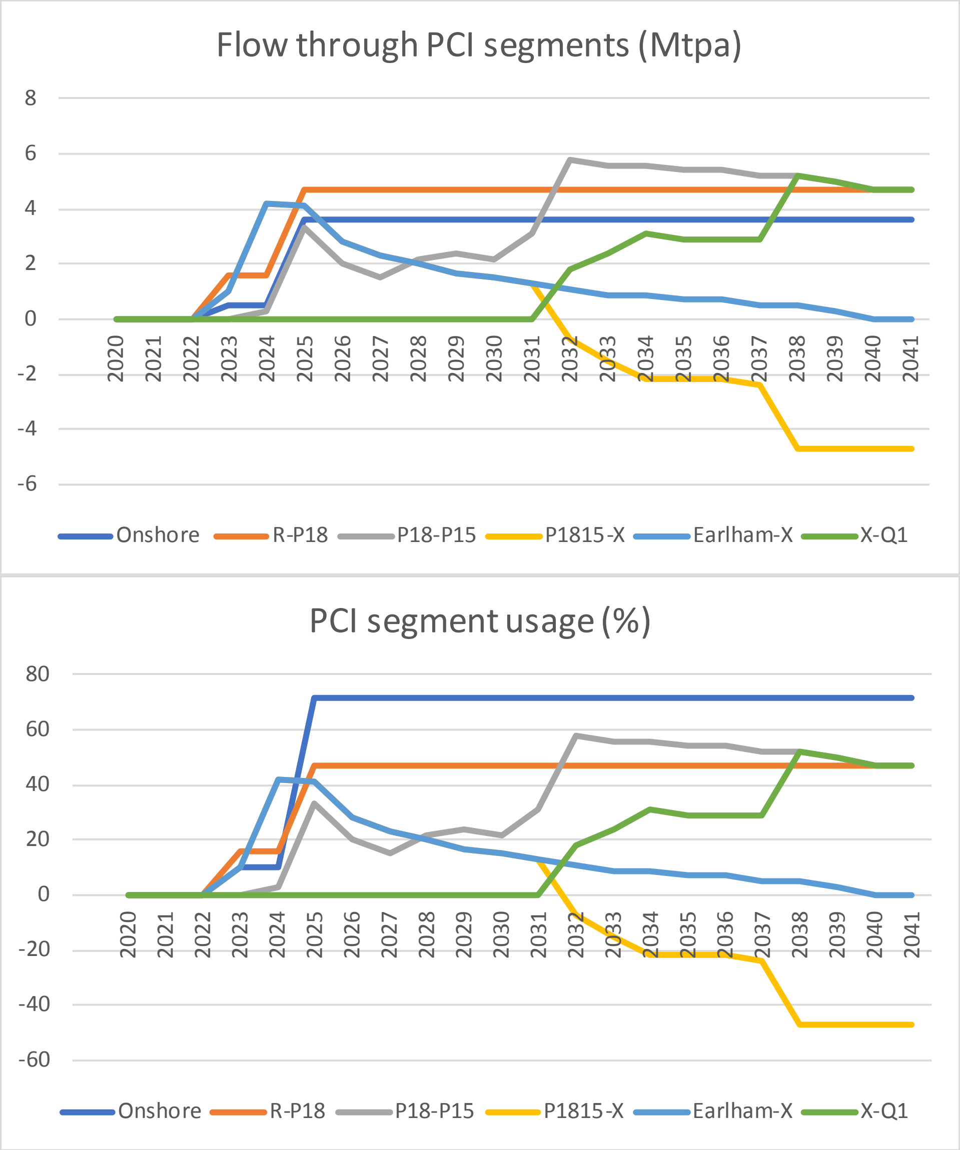

Figure 6: Pipeline usage for the different elements of the Rotterdam Nucleus. Top: flow in Mtpa; bottom: flow in % of pipeline segment capacity. ‘Onshore’: connection with the Rotterdam collection network; ‘R-P18’: pipeline from Rotterdam to P18-A; ‘P18-P15’: connections among the platforms in the P18-P15 cluster of fields (see Figure 4); ‘P1815-X’: the connection between the P18-P15 cluster and the intersection in the Dutch North Sea Trunkline; ‘Earlham-X’: connection between the Earlham and P01-FA fields and the same intersection; ‘X-Q1’: connection between the same intersection and the Q1 store.

b) Risk analysis matrix

Table 10 and Table 11 show the result of a preliminary risk analysis for the Rotterdam Nucleus.

Table 9: Ranking of the risks described in Table 11.

	IMPACT				
PROBABILITY	Negligible	Minor	Moderate	Major	Extreme
Rare			S2, S3	T3	T5
Unlikely			S1, T6, E2	L3, T4, E1	
Moderate			S4	L2, T2	
Likely			T7	T1	L1
Very likely					

Table 10: Risks identified for the Rotterdam Nucleus.

	Risks	Impact	Probability	Mitigation
	Risks - legal			
L1	The London Protocol prevents cross-border CO_2 transport - Article 6 amendment not ratified in time for operation (2022)	Extreme	Likely	Encourage parties to agree amendment / or explore alternative legal options
L2	Member states cannot agree on CO_2 liability arrangements	Major	Moderate	Engage in discussion early to agree terms
L3	Pipeline permitting cannot be completed	Major	Unlikely	Work proactively with authorities
	Risks - social			
S1	Public opposition to onshore CO_2 pipeline	Moderate	Unlikely	Develop timely and proactive engagement plan
S2	Public opposition to offshore CO_2 pipeline	Minor	Rare	Develop timely and proactive engagement plan
S3	Public opposition to offshore CO_2 storage	Minor	Rare	Develop timely and proactive engagement plan
S4	Public opposition to CO_2 capture projects in Rotterdam	Moderate	Moderate	Develop timely and proactive engagement plan
	Risks - Technical			
T1	TAQA decommissions P18-4 well before 2025	Major	Likely	Ensure timely communication
T2	TAQA decommissions P18-A platform before 2025	Major	Moderate	Ensure timely communication
T3	Injection issues in P18-4 field	Major	Rare	Existing FEED studies have developed suitable injection strategies
T4	Leakage risk through abandoned/suspended wells in P18-2	Major	Unlikely	Additional assessment of suspect well clo-

	Risks	Impact	Probability	Mitigation
				sures
T5	Insufficient storage capacity in P18/P15 gas fields	Extreme	Rare	Use production history and existing data to confirm CO_2 capacity
T6	Insufficient storage capacity in Q1 saline aquifer	Moderate	Unlikely	Conducted detailed site characterisation
T7	Planning issues with regards to CO_2 pipeline routes and offshore wind farm developments on the Dutch continental shelf	Moderate	Likely	Engage in early offshore spatial planning
	Risks - Economic			
E1	Costs of pipeline greatly exceeds budget	Major	Unlikely	Complete FEED study with detailed budget
E2	Gas fields Earlham and P1-FA produce less natural gas/CO_2 than forecast	Moderate	Unlikely	Conduct additional field evaluation to reduce uncertainty

3.2 B.2 key performance indicators

Specific criteria, EU 347/2013, Article 4, 2 (e) [6]

a) Avoidance of CO_2 emissions while maintaining security of supply
  i. Reduction of carbon damages: net volume of CO_2 abated over project lifetime (annual and cumulative)

The gross volume stored during the project corresponds to the capture rate in Rotterdam area (Figure 7) and the offshore area (Figure 8). The total gross volume captured and stored during the project is 114.3 $MtCO_2$.

With regards to the net volume of CO_2 abated, the Rotterdam Nucleus transportation infrastructure will lead to CO_2 emission through the use of energy for the compression of CO_2 during transportation. Based on an initial estimate of compression needs for the project, a total of 2.4 $MtCO_2$ in associated emissions has been calculated.

Fugitive emissions from the pipeline and associated infrastructure are expected to negligible. The CO_2 emissions related to the energy needs of CO_2 capture are not included.

The estimated reduction in carbon damages over the 20 year period is therefore **111.9 $MtCO_2$.**

---

[6] See also CBA Methodology Report Sections 3.2.3, 3.2.4, 5.2.5

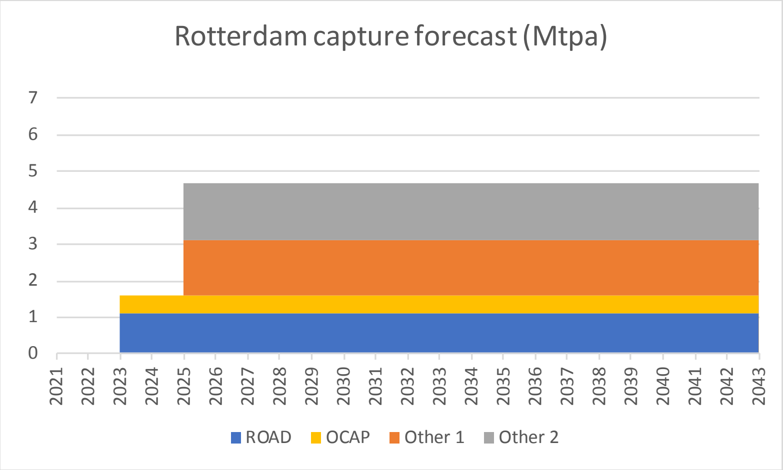

Figure 7: Annual capture in the Rotterdam area for 20 years

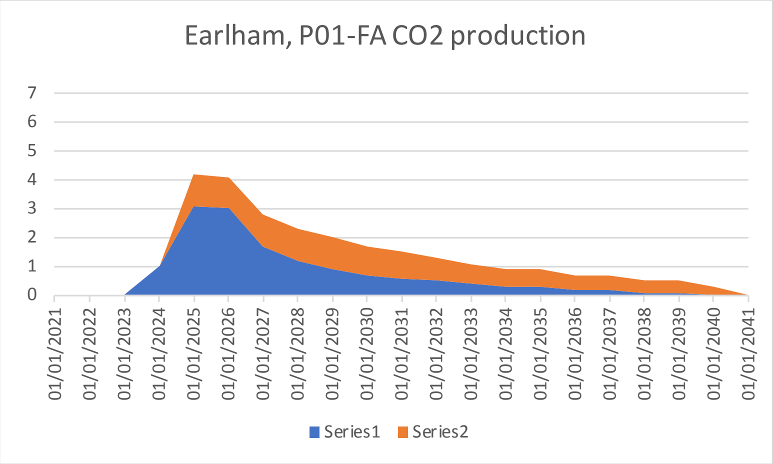

Figure 8: CO_2 production and capture rate in the offshore area

The CO_2 is stored in the P18 and P15 fields and, later, in the Q1 structure. Figure 9 shows the injected volumes in each field, using the current assessment of feasible injection rates. The capacity of the P18 and P15 fields will be reaching its maximum around 2032, at which time the large capacity storage in the Q1 structure will need to be available and operational.

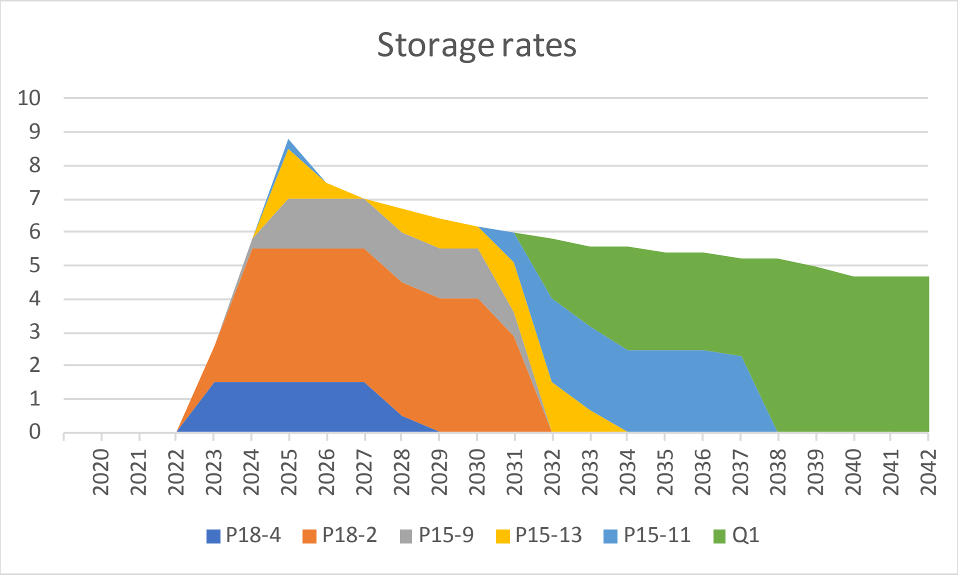

Figure 9: CO_2 storage in the stores connected to the Rotterdam Nucleus. With the data currently available and with the CO_2 supply scenario used, the large capacity of the Q1 store will be used from about 2032.

ii. Security of energy supply and diversification of energy resources

The project supports security of supply by enabling a maintained diversification of power supply while reducing the climate impact of doing so. The project also enables large quantities of natural gas to be extracted from the North Sea while preventing the co-produced CO_2 from entering the atmosphere.

b) Increasing the resilience and security of CO_2 transport

There are currently no CO_2 transport facilities in the Rotterdam harbour capable of transporting large amounts of CO_2 for the purposes of permanent CO_2 storage. There are many industries in the region that have no alternative to make deep emission cuts without the use of CCS. Any developments in the region will therefore increase the resilience and security of CO_2 transport. Furthermore, the oversizing of the Rotterdam CO_2 Gateway and the Dutch North Sea Trunkline, and the pre-identification of future CO_2 storage potential contributes to a resilient and robust CO_2 transport and storage infrastructure capable of securing CO_2 transport for multiple EU Member States.

c) Contribution to the efficient use of resources, by enabling the connection of multiple CO_2 sources and storage sites via common infrastructure and minimising environmental burden and risks

i. Future potential to connect multiple CO_2 sources and storage sites via the proposed common infrastructure

This project is funded by the European Union

Future potential

The Rotterdam Nucleus will form the nucleus of a large-scale CO_2 transport and storage network that is centred on Rotterdam. The Rotterdam Nucleus connects the industrial area of Rotterdam with the vast storage capacity in the North Sea. The current proposal uses the proven store P18-4 drilled from the P18-A platform - which holds the first CO_2 storage permit issued under the EC CCS Directive – as the starting point, from where other nearby stores can easily be reached. The Maasvlakte CCS Project (ROAD) provides the obvious first source of captured CO_2, with many industrial emitters in the Rotterdam area to follow.

The Rotterdam Nucleus is not a point-to-point structure in the form presented, as it connects several emission sources to multiple storage sites and it has the potential of connecting more emission points and more storage locations. The Rotterdam Nucleus is a transport network in itself, with a high potential to become a larger and better connected network in the near future.

Potential for future connections – CO_2 sources / emitters

Once the PCI infrastructure is in place, more emitters than currently described in the PCI application can be connected. The options in the list below are shown in Figure 11.

1. First of all, the Rotterdam Nucleus provides the transport and storage option for emitters in the Rotterdam area. The Port of Rotterdam has been working towards emission reduction in the port area for almost a decade. The current PCI fits well in scenarios set up by the Rotterdam Climate Initiative (Van Engelenburg & Noothout, 2012) and connects to the existing OCAP CO_2 pipeline, which feeds CO_2 from two emitters to greenhouses. A large number of studies, notably those done in the framework of the CATO CCS R&D programme, have looked into the feasibility and cost of capturing CO_2 at a variety of emission points in the Rotterdam area. Industry parties have shown keen interest, as shown by the development of a NER300 application by Air Liquide, in partnership with VOPAK, Anthony Veder and Gasunie in 2013. This project was not continued; the presence of a transport infrastructure for the CO_2 would have significantly improved its business case.
2. The Q1 storage option provides opportunity for emitters near Amsterdam and in IJmuiden (steel plant); an existing oil pipeline between IJmuiden and Q1 could be re-used for CO_2 (see Figure 10, and (EBN-Gasunie, 2010)). This option has been looked into in recent years, as evidenced by the figure, and is currently part of a scenario for the capture, storage and utilisation of CO_2 in the Rotterdam-Amsterdam area of the Netherlands [7]. There will be mutual benefit between the Rotterdam Nucleus and initiatives to reduce the carbon footprint of greenhouses, through the improved business case of the option of offshore storage.
3. Emitters in Antwerp who currently have no options for transporting and storing CO_2 could be connected to the PCI structure. This could be done through ship transport

---

[7] See the CO_2 Smart Grid initiative at https://www.bloc.nl/bloc-works/co2-smart-grid/.

This project is funded by the European Union

between Antwerp and Rotterdam, requiring shipping hubs to be constructed in both locations, or by pipeline. In the latter case, a CO_2 pipeline could follow an existing pipeline corridor between Antwerp and Rotterdam (previously referred to as the CAR pipeline in documents submitted in private to DG Clima and DG Energy in 2015/2016). A potential connection with Antwerp emitters is shown in Figure 11 as either as an onshore pipeline or as a shipping route.

4. Recent studies have investigated the feasibility of connecting the German Ruhr area to the vast storage capacity in the North Sea, by way of barges shuttling between Rotterdam and Germany (CO2Europipe, 2011), although a high-pressure pipeline would be more efficient. This will require the construction of a shipping hub that connects with the offshore pipeline structure.
5. The Earlham and P01-FA fields are the largest two documented of a number of CO_2-rich gas fields. The availability of a CO_2 transport and storage structure offshore will significantly improve the economic viability of exploring and developing such fields [8].
6. The pipeline from Rotterdam out to the Earlham and P01-FA fields will incentivise pipelines from the UK to form a connection with the continent. Such a connection will greatly improve the security not only of supply of storage capacity, by linking UK and NL storage capacity, but also of CO_2 supply, which will improve the business case for storage operators. This will be an important step towards building a stable offshore international CO_2 transport and storage infrastructure, connecting several CO_2 source clusters to several storage clusters.
7. An offshore transport and storage infrastructure can have cross-border impact as far as Le Havre in France. The COCATE project looked into the possibility of linking Le Havre emitters to the North Sea; one of the options was a ship transport link, using a hub in Rotterdam (Coussy, et al., 2013).

---

[8] The reader is referred to online sources of data on offshore hydrocarbon fields, e.g., nlog.nl for data on Dutch fields.

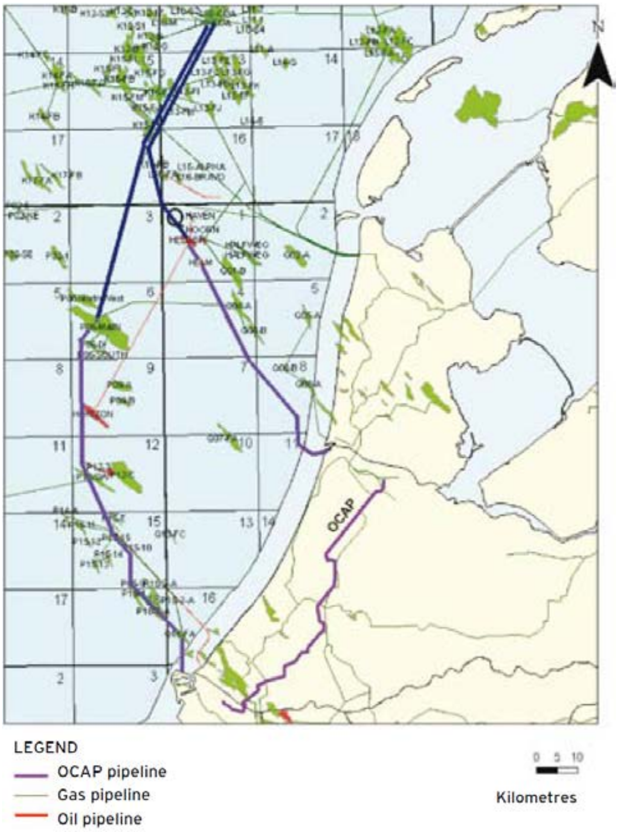

Figure 10: Transport scenario presented by EBN-Gasunie (2010), showing a pipeline from Rotterdam, similar to the current PCI proposal, as well as a pipeline from IJmuiden to the Q1 area. The latter connects emitters near Amsterdam and in IJmuiden to offshore storage capacity. The transport capacity of the pipelines proposed in EBN-Gasunie (2010) is 10 Mtpa.

This project is funded by the European Union

Figure 11: Potential extension of the Rotterdam Nucleus by linking with other emitters or industrial clusters in the region. Numbering corresponds with the numbering in the text, under 'Potential for future connections – CO_2 sources / emitters', heading B.2.c.i. The outline of the Rotterdam Nucleus is shown in the centre of the figure, reproduced from Figure 2.

Potential for future transport capacity

The capacity of the pipelines of the Rotterdam Nucleus is proposed to be 10 Mtpa. During the first few years of operation pipeline use will be well below 100% (see section B.1.l, above). The surplus capacity in this first phase will serve to encourage emitters in the areas listed above to, first, consider CCS as a real option and, second, to start developing capture operations.

Given the current emission level of the Rotterdam industrial area, more than 25 Mtpa (see Figure 12) and the forecast for ETS price increase over the next decades and reducing cost of CO_2 emission abatement (Figure 13), the pipelines could be filled to capacity by as early as 2030 by CO_2 from Rotterdam alone.

The determination of the final size and capacity of the pipelines that make up the Rotterdam Nucleus will be the focus of a more detailed feasibility study as part of the PCI development. Nevertheless, the capacity of 10 Mtpa currently proposed for the PCI is assumed to be a good compromise between oversizing to promote the initiation of capture operations and realising only a fit-for-purpose minimum size pipeline that does not incentivise CCS.

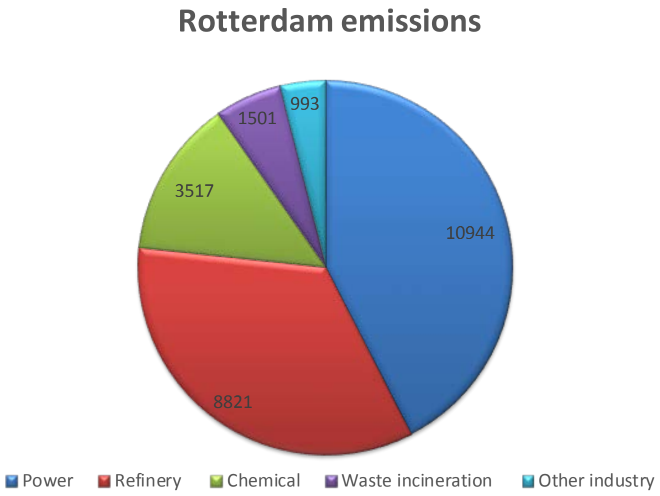

Figure 12: Emission levels in the Rotterdam harbour area, in units of $ktCO_2$.

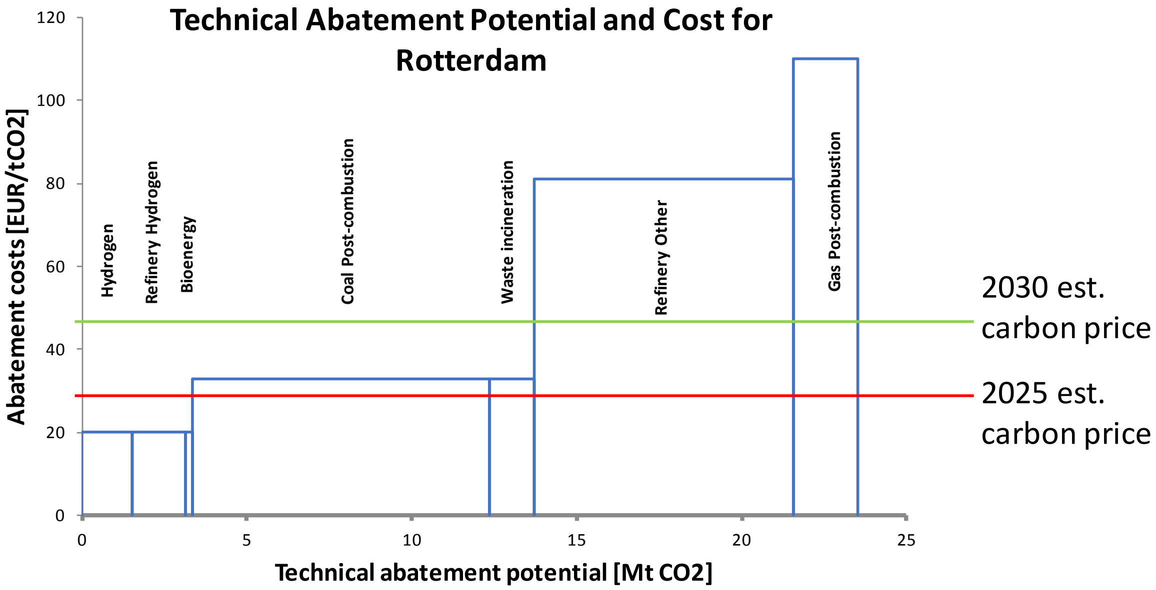

Figure 13: CO_2 emission abatement curve for Rotterdam.[9] Superimposed are expected ETS price levels for 2025 and 2030. By 2025 the lowest-cost abatement options could be below the ETS price level.

---

[9] Marginal abatement cost curve developed in the H2020 Gateway Project

This project is funded by the European Union

Future storage / usage potential

The Rotterdam Nucleus connects emitters in the Rotterdam area with storage opportunities near the coast that are ranked highest with respect to development time and development cost. These include the depleted or almost depleted gas fields in the P18 and P15 cluster and the storage capacity in the Q1 aquifer (Van der Velde, et al., 2008); (EBN-Gasunie, 2010); (Neele, et al., 2011), (Neele, et al., 2012). As described above, the total storage capacity represented by these storage options is about 150 Mt.

Once the PCI transport pipelines are in place, extension of the storage capacity can be found in several directions. Figure 14 shows the approximate location of the options listed below.

1. Directly north of the P01 and Q1 stores lies a multitude of gas fields, of which the majority is expected to reach the end of production by about 2025. The fields in the Dutch offshore K and L blocks are organised in four clusters, each of which has a central, large platform that connects to smaller satellite platforms. Each cluster of fields represents a storage capacity in the range of 150 – 200 Mt of CO_2. The development of these fields and clusters has been studied recently (see, e.g., (EBN-Gasunie, 2010)). The total (theoretical) storage capacity in K and L blocks is of the order of 800 Mt (Neele, et al., 2012).
2. Saline aquifers hold the promise of large to very large storage capacity (e.g., (Vangkilde-Pedersen, et al., 2009)); the key example of saline aquifer storage is the Sleipner project in Norway. However, the lead time of developing storage locations in saline aquifers is longer than that of depleted gas fields (Neele, et al., 2012) and the risk of not finding suitable storage space is significant. However, a CO_2 pipeline bringing CO_2 close to a potential, large storage site in a saline formation changes the situation. A potentially large capacity saline formation (360 Mt) was identified in the P and Q blocks in the Dutch offshore (Neele, et al., 2012). Once CO_2 is available offshore, the cost and risk of exploring and developing this structure will be lower than for a remote aquifer, with no nearby CO_2 infrastructure. The PCI will thus stimulate the exploration (testing) and development of this storage structure.

3. The UK offshore close to the Earlham field has a large number of gas fields, many of which offer potential storage capacities larger than about 50 MtCO_2, which can be relatively easily to the transport infrastructure at Earlham or P01-FA. Further afield, a future extension of this network towards the Humberside region of the UK would provide access to a large emission cluster and the necessary additional storage capacity that would be required. Risk mitigation in CCS is provided through access to a multi-source, multi-sink system.

   The Humberside cluster contains a series of large CO_2 emitters in the steel, power, refinery, glass, cement and paper sectors, with current emissions in excess of 20 Mte/annum.

   In 2016 the Energy Technologies Institute undertook the UK Storage Appraisal Project which produced the UK's first CO_2 storage appraisal database 10. This web-enabled

---

[10] See www.co2stored.co.uk, and (Pale Blue Dot, 2016)

This project is funded by the European Union

database - the first of its type anywhere in the world - contains geological data, storage estimates, risk assessments and economics of nearly 600 potential CO_2 storage units of depleted oil and gas reservoirs, and saline aquifers around the UK. It enables interested stakeholders to access information about the storage resource and to make more informed decisions related to the roll out of CCS in the UK. In particular this appraisal identified some very promising future CO_2 storage sites in the area between the Earlham field and the Humberside cluster in the UK. This includes two of the top five ranked sites for future development that were subject to detailed appraisal in this study:

- The depleted Viking A gas field: assessed at 130 Mte storage capacity
- Bunter Closure 36: assessed at 280 Mte storage capacity

4. The NL offshore area also presents options for CO_2 use. The Rijn oil field in the P15 block offers an opportunity for enhanced oil recovery. The Rijn field is shown in Figure 4 as the green outline under the P15-ACD platform.
   The field is currently producing with ESPs at high water cut and water is reinjected for pressure support. The feasibility of CO_2 EOR at Rijn has not been studied, but the potential prize is large. The current recovery of original oil in place is low, around 20%, after water flooding and ESP deployment. When CO_2 is available in the P18 and P15 blocks, the economic viability of CO_2-EOR becomes a real option.
   Other offshore oil fields in the NL offshore sector are probably too small, even when CO_2 is available offshore.

This project is funded by the European Union

Figure 14: Potential extension of the Rotterdam Nucleus to other potential storage locations. Numbering corresponds with the numbering in the text, under Future storage / usage potential', heading B.2.c.i. (Section 3.2) The yellow outlines indicare the approximate location of the various storage options. The outline of the Rotterdam Nucleus is shown in the centre of the figure, reproduced from Figure 2.

ii. Extension of the economic or regulatory lifetime of existing assets

In many situations offshore, the first injection of CO_2 will occur at the same time as existing hydrocarbon production from neighbouring wells, since in many cases in the Dutch continental shelf it has been possible to reach more than one reservoir/field from a platform. The possibility of reusing North Sea natural gas production assets (platforms/wells) for CO_2 storage can lead to considerable economic savings over decommissioning and then rebuilding/drilling.

This is the case with the P18-A platform located 20km offshore Maasvlakte. Three pressure independent fields drilled from this platform are producing today, though they are each approaching the end of their producing life as reservoir pressure declines to a point where production rates fall below economic levels and formation water starts to gather at the bottom of each well and starts to interfere with well productivity.

One scenario is that the fields cease production one by one in 2018, 2020 and 2022. Without CO_2 storage, the next logical step would be to plan for decommissioning. It is most efficient

This project is funded by the European Union

to suspend individual wells as they cease producing and then wait to decommission wells and platform together in a coordinated programme. If we assume that decommissioning of the P18-A platform and wells will be independent of a larger regional decommissioning programme, then a plan to decommission P18-A might be submitted for approval in 2022, with decommissioning of the wells conducted in 2024, and removal of the deck and jacket in 2025.

Part of the proposal to decommission would include evaluation of alternative uses of the infrastructure, and an explanation why, on balance, removal is preferable. Decommissioning of the 6 existing wells drilled from the P18-A platform could cost €15 million and removal of the deck and jacket another €5 million. (all costs are estimates without background study to take account of specific situations). Subsequently installing a new CO_2 injection platform could cost €30 million for a 4 well slot, zero facilities installation. If compression is required offshore for injection and onward transport then a much larger platform would be required, most likely more than doubling the cost. Drilling 3 new injection wells, one in the P18-4 field (8 Mt capacity) and two in the P18-2 field (32 Mt capacity), could cost another €25 million each.

This investment would not take place until some-time after removal of the existing facilities, hence first injection could take place from 2030. Retaining the existing facilities and converting three wells for CO_2 injection will cost an estimated €5 million per well plus €20 million for platform modifications. The existing wells are ready for conversion to injection immediately. Following construction of the connecting pipeline first injection could take place in 2021 (originally planned for 2015 under EEPR funding to ROAD).

Estimated cost in the case of decommissioning of potentially reusable natural gas infrastructure at P18-A, followed by the new installation of CO_2 storage infrastructure:

- 2024-2025 decom €20 million
- 2028-2030 new wells and platform €105 million
- Inject from 2030
- Decommission this new equipment in 2045 for €15 million

Total cost - €140 million

Or

Estimate costing of converting existing natural gas infrastructure at P18-A to CO_2 storage infrastructure.

- 2018-2020 convert existing €35 million
- Inject from 2020
- Decommission cost of €20 million delayed to 2035 perhaps

Total cost - €55 million, difference €85 million.

This project is funded by the European Union

This P18 estimate is an example of a comparison field by field that can be made across the Dutch and UK Southern North Sea.

3.3 B.3 cost-benefit analysis

PROJECT-SPECIFIC ANALYSIS OUTPUT

The methodology for CAPEX and OPEX calculations used in the CBA, calculation of benefits, and the assumptions used both for the project-specific analysis and socioeconomic analysis are presented in Section 4.

a) Project-specific analysis indicators

i. Financial Net Present Value

The financial NPV for the project is **€-56.3m.**

In Figure 15 the cashflow of the Rotterdam Nucleus project is provided. The revenues related to the charge of tariffs for CO_2 transportation from the Earlham and P01-FA gas fields. At the start of the project a relatively large investment is needed, and a relatively small operational cost afterwards.

There is no capital grant or income assumed at this stage, which results in a negative NPV (€-56.3m). In Table 4 more details are given of the most important KPI's including NPV and total CAPEX and OPEX. Moreover in Figure 16 and Figure 17 shows the impact of a governmental grant on the NPV and the value of the grant itself. The result shows that if around 30% of the total investment is supported, the NPV starts to become a positive value and an NPV allowing commercial investment in the project can be achieved at an investment support level of 40% - 50%. This corresponds to 130 - 160M€.

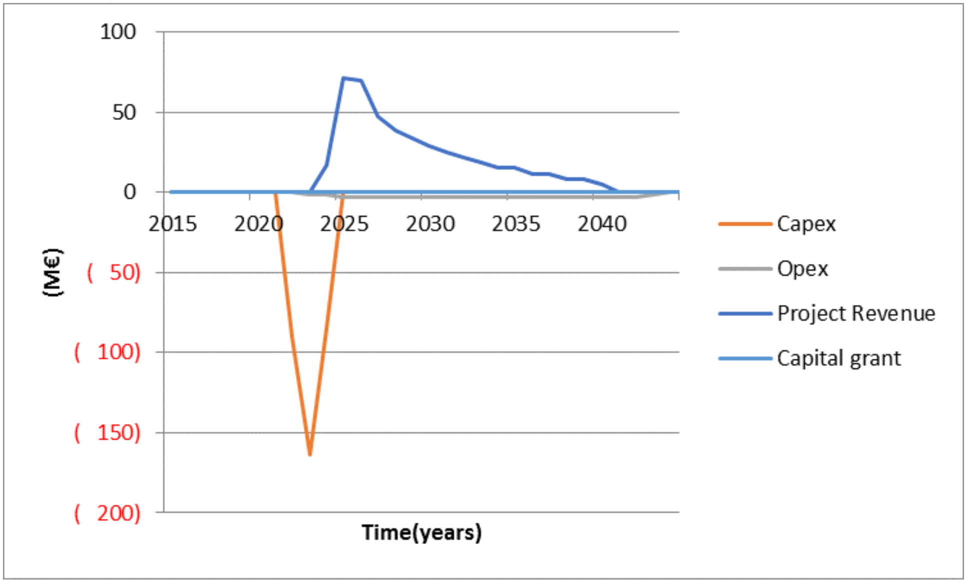

Figure 15: Cashflow of the transport

This project is funded by the European Union

Table 11: Summary income and cost statement for transport

Summary Transport Income Statement (Total EURm unless otherwise stated, 2016 Basis)	
Cost per tCO_2 Transported	€3,48
Revenues (Earlham/P01-FA)	€450,5m
Total OPEX	-€59,4m
OPEX/Total CO_2 transported	*(€0,5 /tCO_2)*
Total CAPEX	-€338.3m
CAPEX/Total CO_2 transported	(€3,0 /tCO_2)
Net Present Value Cash Flows to Equity (Disc. @ 8%)	-€56,3m

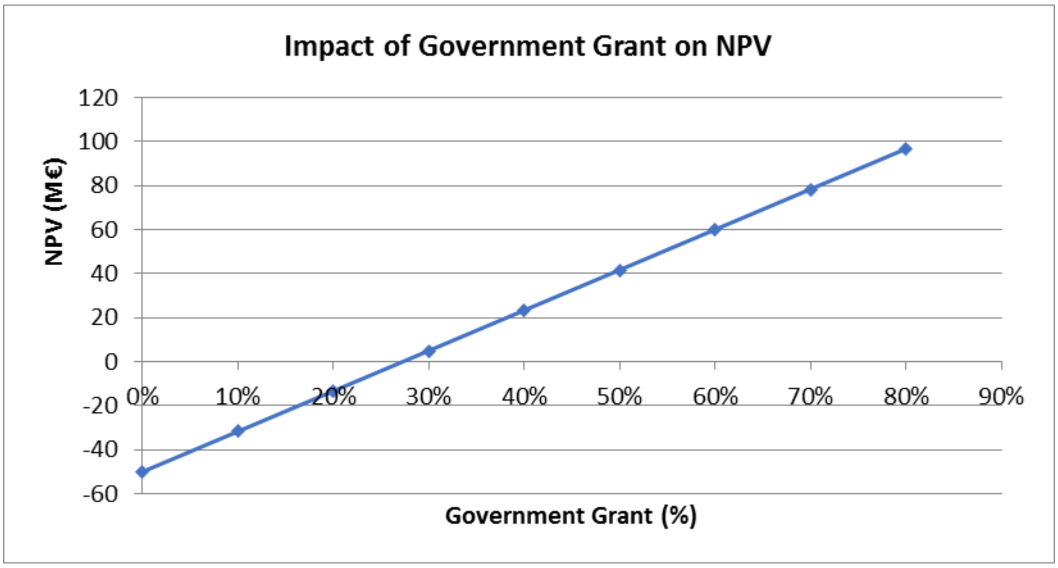

Figure 16: Impact government grant on NPV

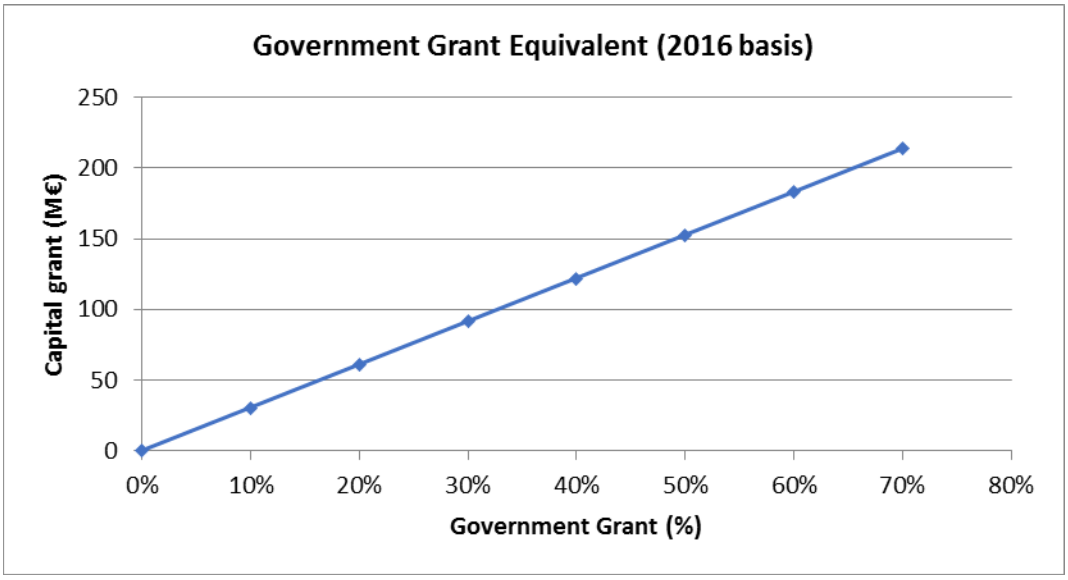

Figure 17: Value of Government Grant

ii. Financial Internal Rate of Return

The financial internal rate of return for the project is **1.6%.**

iii. Financial Benefit-Cost Ratio

The economic benefit cost ratio is: NPV/Investment is equal to: -56,3/338 = **-17%.**

iv. Applied Financial Discount Rate

The applied discount rate is **8%.**

v. Present value of CO_2 transport-related financial revenues

The NPV of the project **-€56,3.**

vi. Capital and operational expenditure per year over project lifetime

Table 12: Total capex and opex of all PCI elements

Start Date	Capex	Opex
(dd.mm.yyyy)	(M€)	(M€)
Total	(338)	(59)
1-1-2022	(90)	0
1-1-2023	(164)	(1)
1-1-2024	(84)	(1)
1-1-2025	0	(3)
1-1-2026	0	(3)
1-1-2027	0	(3)
1-1-2028	0	(3)
1-1-2029	0	(3)
1-1-2030	0	(3)
1-1-2031	0	(3)
1-1-2032	0	(3)
1-1-2033	0	(3)
1-1-2034	0	(3)
1-1-2035	0	(3)
1-1-2036	0	(3)
1-1-2037	0	(3)
1-1-2038	0	(3)
1-1-2039	0	(3)
1-1-2040	0	(3)

This project is funded by the European Union

Start Date	Capex	Opex
1-1-2041	0	(3)
1-1-2042	0	(3)
1-1-2043	0	(1)
1-1-2044	0	0

SOCIOECONOMIC ANALYSIS OUTPUT

b) Socioeconomic analysis indicators

i. Economic Net Present Value

The socioeconomic analysis is based on a tariff of 60 €/tonne CO_2 and a discount rate of 3%. These new assumptions results in a relatively large revenue (see Figure **18**) and relatively large NPV (Table **14**)

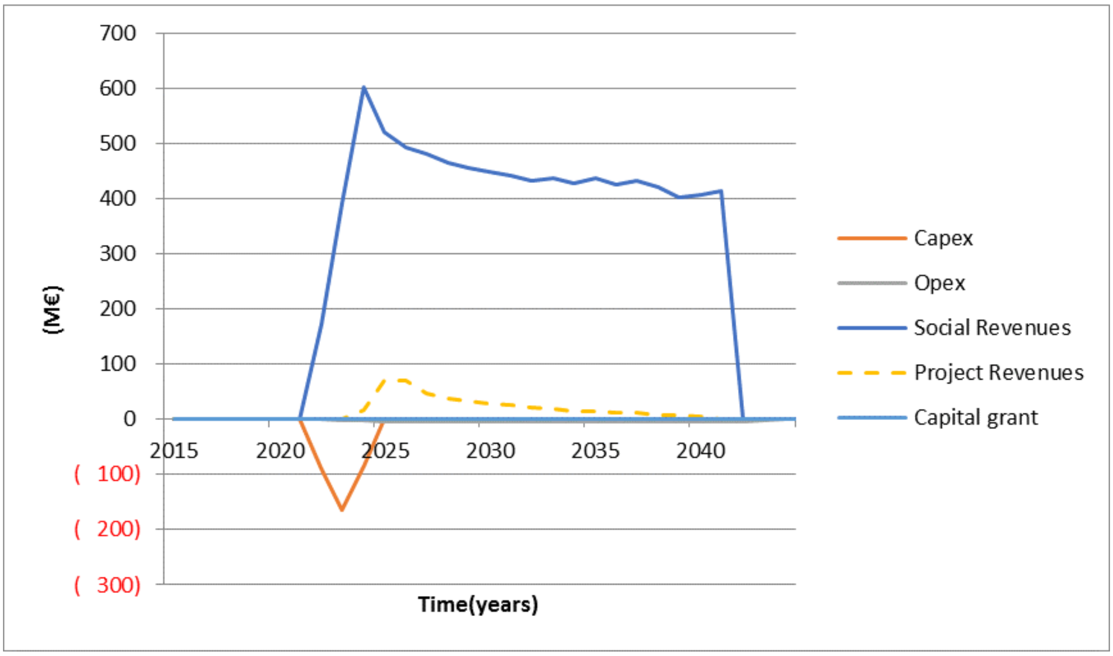

Figure 18: Social project cashflow

Table 13: Summary social income and cost statement for transport

Summary Transport Income Statement (Total EURm unless otherwise stated, 2016 Basis)	
Cost per tCO_2 Transported	3,48
External contribution (Earlham/P01-FA)	€450,5m
Total OPEX	-€59,4m
OPEX/Total CO_2 transported	*(€0,5 /tCO_2)*
Total CAPEX	-€338.3m
CAPEX/Total CO_2 transported	*(€3,0 /tCO_2)*
Net Present Value Cash Flows to Equity (Disc. @ 3%)	€5262.0m

ii. Economic Internal Rate of Return

The social economic internal rate of return is 174% for all transport segments.

iii. Economic Benefit-Cost Ratio

The economic benefit cost ratio is: NPV/Investment is equal to: 5262/338= **1557%** for all segments.

iv. Present value of total anticipated benefit, i.e. present value of the total social value of mitigated CO_2 emissions

The social economic NPV is equal to €5262.0m

c) Share of benefits by project country

The volumes provided by each country is given in Figure 19.

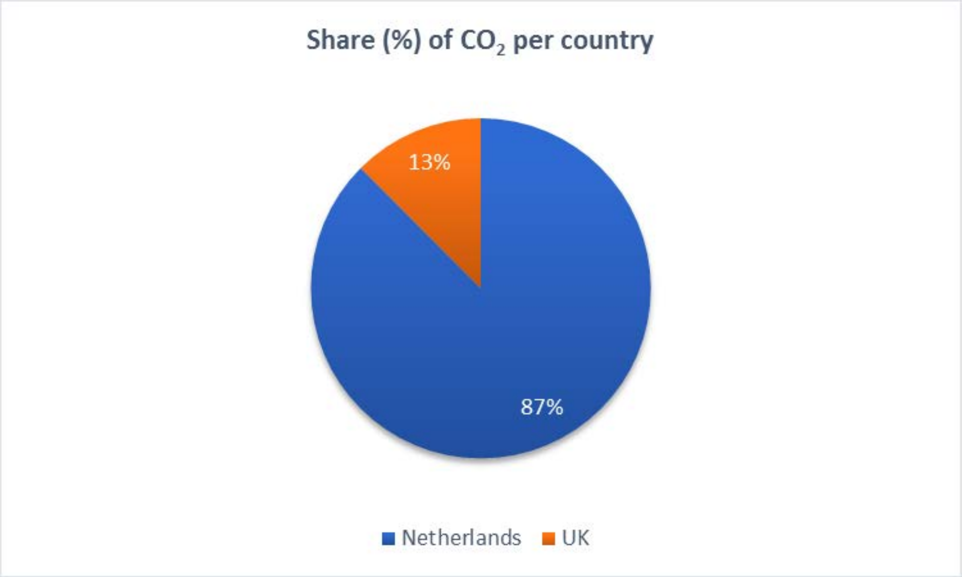

Figure 19: Share of benefits per country

The total societal benefit associated with CO_2 reduction in the United Kingdom is €0.89 billion.
The total societal benefit associated with CO_2 reduction in the Netherlands is €5.95 billion.

d) Volume of CO_2 transported over project lifetime (annual and cumulative)

During the first 20 years of the project the following volumes of CO_2 are transported (see Table 15).

Table 14: Volume of CO_2 transported

Time	Annual	Cumulative
Year	Mt	Mt
2021	0	0
2022	0	0
2023	2,6	2,6
2024	5,8	8,4
2025	8,8	17,2
2026	7,5	24,7
2027	7	31,7
2028	6,7	38,4
2029	6,4	44,8
2030	6,2	51
2031	6	57

This project is funded by the European Union

Time	Annual	Cumulative
2032	5,8	62,8
2033	5,6	68,4
2034	5,6	74
2035	5,4	79,4
2036	5,4	84,8
2037	5,2	90
2038	5,2	95,2
2039	5	100,2
2040	4,7	104,9
2041	4,7	109,6
2042	4,7	114,3

e) Volume of CO_2 transported per unit of capital expenditure

In Table 14 this KPI is given and is equal to (€3,0 /tCO_2).

f) Notable positive externalities

- First-of-a-kind high pressure/high volume CO_2 transportation pipeline in the EU.
- Availability of CO_2 transport to considerable offshore storage capacity will encourage uptake of CO_2 capture.
- Employment created during the construction and operation phase of pipeline.
- Employment preserved in industries which are able to decarbonise through CCS, particularly in refining, chemical and waste incineration industries where no other near-term mitigation options are forthcoming.

g) Notable negative externalities

- Potential disruption to environment and society during construction phase.

This project is funded by the European Union

4 SUPPLEMENTARY INFORMATION ON COST-BENEFIT ANALYSIS

Calculation of project costs

The capital and operation costs of the Rotterdam Nucleus, used in the CBA, have been calculated using the ECCO Tool (Løvseth & Wahl, 2012). ECCO Tool is a software program designed to evaluate quantitatively the post-tax economics of Carbon Capture and Storage (CCS) projects for each of the mutually dependent actors along the CCS value chain. The main objective of ECCO is to facilitate robust strategic decision-making regarding early and future deployment of CO2 value chains.

The tool is designed to have a level of detail that is appropriate for studying the economic feasibility of well-defined CCS projects to be executed by commercial companies, studying whether or not to invest in (part of) the value chain and, if so, under which contractual conditions. The tool integrates cost engineering, transport and well/reservoir physics, planning (including the impact of contracts and physics on the sizing and timing of capex and opex), and full post-tax economics (including macro- and micro-economics).

In the cost benefit analysis presented here only the transport and more specific the pipeline module is used. Pipeline transport costs are determined by the following key cost factors:

- Pipeline routing: determines the length of the pipeline and whether it is routed onshore or offshore;
- Diameter, material and wall thickness: depending on the volume to be transported and the required pressure the model calculates the optimal diameter and wall thickness to secure safe operation;
- Terrain covered by pipeline: Terrain factors are used to allow for cost inflation due to complex terrain conditions. Heavy industrialised and densely populated areas have typical higher capital investments for pipelines. Costs increase in heavily urbanized areas because of accessibility to construction and additional required safety measures. Complex terrain conditions like hilly areas and soggy or unstable soil may also increase the investment costs considerably;
- Art works, crossings and any umbilical control: specific cost factors are included for land fall and for art works if a pipeline crosses existing infrastructure. The amount and type of art works can be varied by the user. Costs for art works can go up to €4-8 million per artwork. Cost of land fall (onshore to offshore crossing or vice versa) also significantly adds to the total capital investments at about €7 million per crossing. The crossing of waterways/shipping lanes is also included.

Based on these variables the model calculates the capital investments and the annual operation and maintenance cost broken down into the following line items:

- Material costs (steel cost): the diameter and wall thickness determine the amount of steel used which together with a steel price yields steel costs;

This project is funded by the European Union

- Labour cost (installation costs): a fixed per km price is assumed for the cost of labour;
- Construction costs (material/equipment costs and installation costs);
- Other costs: e.g. design and engineering, project management, regulatory filing fees, insurance costs, and right-of-way costs are assumed to be covered within a fixed cost factor per km pipeline;
- Art works, crossings and any umbilical control;
- Offshore capital includes specific requirements for offshore pipelines: capital costs cover platform tie in, shallow installation, heavy lift, dredging, marine survey, transportation, umbilicals and additional material requirements (coating/concrete). The costs are included as one cost factor amounting to €0.95m/km. An exception is the offshore platform tie-in which is specified as a length-independent capital investment of €16 million;
- Operation and maintenance costs (monitoring, operation, maintenance): the O&M costs are broken down into fixed costs and variable costs. The fixed costs are expressed as an annual % of capital investments (0.25%) which should be added to variable cost of €0.3/tCO_2.

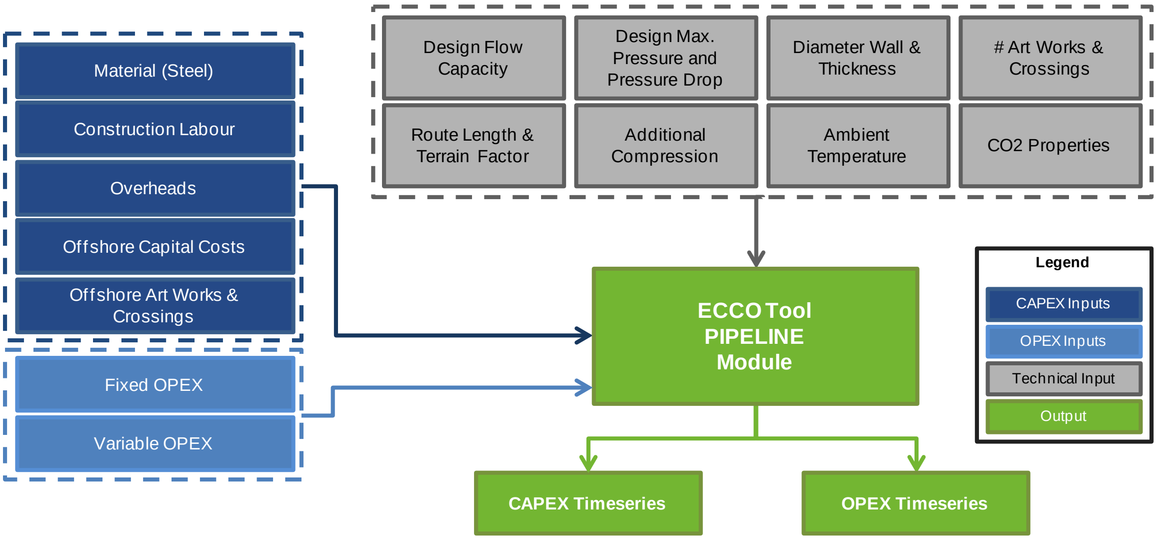

Figure 20: ECCO tool Pipeline Module Structure (Inputs & Outputs)

Table 15: ECCO tool Pipeline Module CAPEX and OPEX Assumptions

	Value	Reference
CAPEX		
Materials –steel	$\pi * L * t * (D - t) * \rho * Pr$	L=Length t=wall thickness D= pipeline diameter (outer) ρ = steel density (7850 kg/m^3) Pr =steel price (600 €/tCO$_2$)
Labour	0.120 €m /km	ECCO 2011
Overheads	0.102 €m /km	ECCO 2011
Offshore Capital	0.95 €m /km	ECCO 2011, adapted based on NOGEPA 2008/2009
Offshore infrastructure crossing	4-8 €m	NOGEPA 2008/2009
Offshore waterway crossing	11-16 €m	NOGEPA 2008/2009
Land fall	7 €m	NOGEPA 2008/2009
OPEX		
Fixed OPEX	0.25% of CAPEX	ZEP 2011;ECCO 2011
Variable OPEX	0.29 €/tCO$_2$	ZEP 2011; ECCO 2011

Financial assumptions

The financial assumptions used in the CBA and Social Economic Analysis follow the requirements of the ‘Cost-benefit analysis methodology and PCI application template’ document prepared by Ramboll and Ecorys, see Table 17.

Table 16: ECCO tool financial assumptions.

Parameter	Value
Time horizon	20 years
Inflation **rate**	1.5%
Tax rate	0%
Financial discount rate	8%
Social discount rate	3%
Social cost of carbon	€60/tCO$_2$

- only cash inflows and outflows, in other words cash revenues and expenditures, are included in the analysis. Items such as depreciation, reserves, interest, loan repayments are excluded
- Direct taxes are excluded

Assumption of benefits used in CBA

The Rotterdam Nucleus project derives financial revenues through the provision of transportation routes for CO$_2$ separated from high CO$_2$ content gas fields, Earlham (UK) and P01-FA

(NL). The exploitation of these gas fields would be commercial investments made outside the scope of the PCI. The investments for the development of the fields, platform constructions, wells, gas processing and gas evacuation pipelines would be made by commercial parties. The licence for the Earlham field is held by Swift Exploration Ltd, an affiliated applicant of the Rotterdam Nucleus project.

Individual cashflow analyses have been conducted for the exploitation of these gas fields, in order to ascertain the value that could be transferred to the Rotterdam Nucleus project. It has been agreed in principle with Swift Exploration Ltd that without suitable CO_2 transport infrastructure linking the Ealham, and potentially the P1-FA field, to the P18-4 CO_2 storage site, the exploitation of the high-CO_2 content gas fields could not proceed. In light of this, it has also been agreed in principle that the eventual developer of the gas fields would be willing to pay an transport tariff per tonne of CO_2 transported, that is higher than the marginal transportation costs of that particular segment of pipeline (the Dutch North Sea Trunkline).

To ascertain a suitable figure for this elevated transport tariff, a cashflow analysis allowing the developer to cover capital and operation cost (including a fee for storage), plus an IRR of 20% was conducted for both the Earlham and P1-FA fields. The results suggest that in addition to covering costs and achieving a 20% IRR, sufficient value would be generated allowing a value of €17/tCO_2 transported through the Dutch North Sea Trunkline to storage locations in P18 and P15 on the Dutch continental shelf. The total revenue over the 20 project period amounts is calculated to be €450,5m. This revenue for the use of the Dutch North Sea Trunkline contributes to the CBA of the entire Rotterdam Nucleus Project.

This project is funded by the European Union

5 CONCLUSIONS

This report presents the outline of the Project of Common Interest (PCI) on CO_2 transport that was developed in the H2020 GATEWAY project. The PCI is centered on the Rotterdam industrialised region of the Rotterdam harbour in The Netherlands. This region is responsible for a significant part of the total greenhouse gas emissions in The Netherlands. The Rotterdam area already has a CO_2 transport pipeline that delivers CO_2 from two sources of pure CO_2 to greenhouses. The Rotterdam harbour is also home to the Rotterdam Maasvlakte CCS Project (ROAD), which is the one remaining flagship project funded by the EERP programme.

The ‘Rotterdam Nucleus’ has good potential for future growth, on the CO_2 supply side, as well as on the CO_2 storage side, and can deliver the first elements of a North Sea CO_2 transport and storage infrastructure.

This project is funded by the European Union

6 BIBLIOGRAPHY

CO2Europipe, 2011. *D4.2.2 Making CO2 transport feasible: the German case - Rhine/Ruhr are (D) - Hamburg (D) - North Sea (D, DK, NL),* CO2Europipe consortium.

Coussy, P., Roussanaly, S., Bureau-Cauchois, G. & Wildenborg, T., 2013. Economic CO2 network optimization model COCATE European project (2010-2013). *Energy Procedia,* Volume 37, pp. 2923-2931.

EBN-Gasunie, 2010. *CO2 transport and storage strategy.*

European Comission, 2016. *EU Reference Scenario 2016,* Brussel: European Commission.

Eurostat, 2017. *Energy from renewable sources.* [Online]
Available at: http://ec.europa.eu/eurostat/web/energy/data/shares.

Løvseth, S. W. & Wahl, P. E., 2012. ECCO Tool: Analysis of CCS value chains. *Energy Procedia,* Volume 23, p. 4.

Neele, F., Hofstee, C., Dillen, M. & Nepveu, M., 2011. *Independent storage assessment of offshore CO2 storage options for Rotterdam - Summary report,* Utrecht: TNO.

Neele, F., Ten Veen, J., Wilschut, F. & Hofstee, C., 2012. *Independent assessment of high-capacity offshore CO2 storage options,* Utrecht: TNO.

NSBTF (North Sea Basin Task Force), NSBTF strategic regional plan on CCS transport infrastructure, 2017.

Offshore Magazine, 2013. *North Sea offshore oil and gas map,* Houston: Offshore Magazine.

Pale Blue Dot, 2016. *Progressing development of the UK's strategic carbon dioxide storage resource – a summary of results from the strategic UK CO2 storage appraisal project.*

Ros, M. Read, A., Uilenreef, J., and J. Limbeek, 2014. Start of a CO2 Hub in Rotterdam: Connecting CCS and CCU. *Energy Procedia,* Volume 63, p. 11.

Rütters, H., 2013. *State of play on CO2 geological storage in 28 European countries. CGS Europe report No. D2.10, June 2013, 89 p.*

Van der Velde, R., Mieog, J., Breunese, J. & Remmelts, G., 2008. *Potential for CO2 storage in depleted gas fields on the Dutch continental shelf.*

Van Engelenburg, B. & Noothout, P., 2012. *Rotterdam CCS cluster project – Case study on lessons learnt, Rotterdam Climate Initiative.*

Vangkilde-Pedersen, T. et al., 2009. Assessing European capacity for geological storage of carbon dioxide–the EU GeoCapacity project. *Energy Procedia,* Volume 1, pp. 2663-2670.

Wuppertal Institute for Climate, E. a. E., 2016. *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam ,* Wuppertal: Wuppertal Institute for Climate, Environment and Energy.