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Start of a CO_2 hub in Rotterdam: connecting CCS and CCU

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Abstract

Rotterdam is an industry intensive region with the ambition of combining economic growth with sustainable development. It set itself the target to reduce annual CO_2 emissions with 50% by 2025 compared to 1990 levels (a 27 Mt reduction compared to business as usual). CCS is projected to play a big role in reaching this target, providing 60-70% of the reduction. The ROAD project aims to capture 1.1 Mt/yr on average at a new build coal fired power plant (Maasvlakte Power Plant 3, MPP3) on the Maasvlakte/Rotterdam. There is also a possibility to re-use (CCU) part of this captured CO_2 in greenhouses north of Rotterdam. OCAP currently delivers CO_2 from a refinery and bioethanol plant to greenhouses to enhance crop growth. This is seasonal demand, so the CO_2 sources emit the CO_2 in the winter. ROAD and OCAP have investigated the possibility to connect the two infrastructures and thereby creating a CO_2 hub in Rotterdam, giving additional CO_2 delivery to greenhouses in summer and additional CO_2 storage in winter. The main challenge is the sizing, design and operation of the infrastructure, an 18 km pipeline. A 20” or 24” pipeline operated at 21 bar seems to be the best option. Between these two pipelines the only distinction is the throughput (and therefore fit with ambitions of CCS and CCU). With a marginal additional investment the throughput increases by 50-60% between a 20” and 24” pipeline. Another advantage of using a 21 bar pipeline to connect the system is the possibility to control the temperature in the ROAD pipeline to the storage site.

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1. Introduction

Rotterdam is a major industrial and carbon intensive region as well as Europe's largest port. Recognizing the need to combine economic growth with sustainable development, the region set itself the target to reduce CO_2 emissions with 50% by 2025 compared to 1990 levels (a 12Mt[†] reduction from 1990 levels and a reduction of 27 Mt from business as usual forecasts for 2025). CCS plays a big role in reaching this target providing 60-70% of the total reduction, including a forecast 5.5Mt from industrial sources (see Fig. 1).

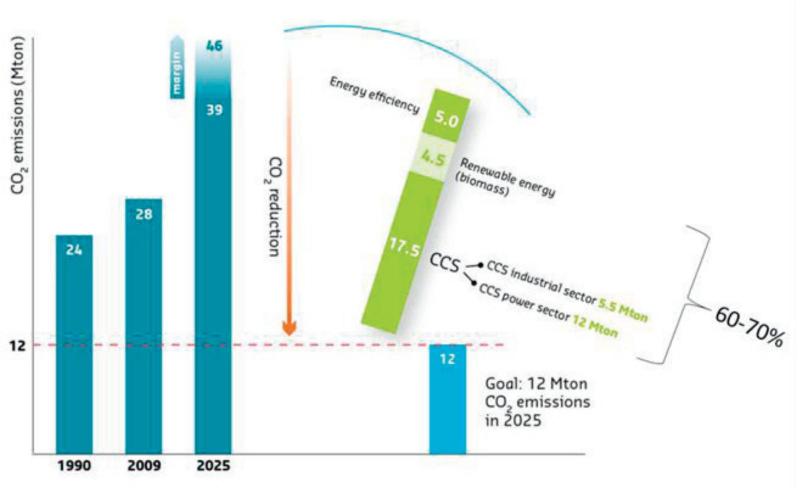

Fig. 1. RCI CO2 reduction target for 2025 compared to 1990 levels.

The Rotterdam port and industrial area has a number of advantages that create favourable conditions for implementing CCS on an industrial scale:

- the presence of several industrial CO_2 point sources
- several new carbon-capture-ready power stations and other industrial plants under construction
- Dutch experience with gas production and gas storage
- sufficient offshore gas reservoirs in the vicinity that are geologically and physically suitable for CO_2 storage and almost at the end of their economic lifecycle, allowing for small transport distances and
- options to develop facilities for the liquefaction and shipping of CO_2 for use for Enhanced Oil Recovery

Another aspect of the Port of Rotterdam sustainable development vision is to become a "bio-port". In addition to acting as a simple transport hub, the port actively encourages investment in facilities to process raw biomass (brought in by ship) into biofuels and bio-chemicals for use across northern Europe.

1.1. The ROAD project: CS in Rotterdam

ROAD is the Rotterdam Opslag and Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project), one of the largest integrated Carbon Capture and Storage (CCS) demonstration projects in the world. It is widely recognized as the most promising CCS project in Europe. The ROAD project is co-financed by the Government of the Netherlands and the European Commission within the framework of the European Energy

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[†] Note, throughout this paper t refers exclusively to metric tonnes (=1 000kg) and Mt to a million metric tonnes. Short tons are not used.

Programme for Recovery (EEPR). In addition, the Global CCS Institute is knowledge sharing partner of ROAD and has given financial support to the project.

Within overall climate policy CCS will play an important role in reducing CO_2 emissions. CCS is part of the long term European energy policy and it is widely assumed that a competitive low carbon energy mix needs to include CCS. Accordingly, CCS is on track to become one of the key technologies for combating climate change. Increasing carbon prices, political commitment to CCS and opportunities for Enhanced Oil Recovery (EOR) should make CCS commercially viable in the near future.

ROAD aims to demonstrate the technical and economic feasibility of deploying CCS on a large scale as well as the decarbonization of electricity generated from fossil fuels. In addition, ROAD will test policymakers' willingness to enable CCS as a viable technology through advocacy for CCS-stimulating measures (e.g. Green Premium). Within 5 to 10 years the knowledge developed by ROAD's demonstration project will be highly significant in the broader deployment of CCS in Europe.

ROAD applies post combustion technology to capture the CO_2 from the flue gases of a new 1,100 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the port and industrial area of Rotterdam. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 million tonnes of CO_2 per year. The capture installation is planned to be operational in 2018.

From the capture unit the CO_2 will be transported through a pipeline: 5 kilometers over land and 20 kilometers across the seabed to the existing P18-A platform in the North Sea. The pipeline has a transport capacity of around 5 million tonnes per year. ROAD plans to store the captured CO_2 in depleted gas reservoirs under the North Sea. These gas reservoirs are located in block P18 (P18-6, P18-4 and P18-2) of the Dutch continental shelf, approximately 20 kilometers off the coast, with an estimated total storage capacity of 35 million tonnes. The depleted gas reservoirs are at a depth of around 3,500 meters under the seabed. The existing platform will be reused for CO_2 injection.

1.2. OCAP: Existing CCUS in Rotterdam

There is an existing CCU (carbon capture and use) system in Rotterdam making use of CO_2 already captured in industrial processes in the port to help reduce carbon emissions by greenhouse owners. The system is operated by OCAP (www.ocap.nl), a subsidiary of Linde Gas. OCAP is Organic Carbondioxide for Assimilation of Plants, and supplies pure CO_2 by pipeline from industry in the Rotterdam port area to greenhouses north of the port (area is called Westland). In 2005 OCAP started delivering CO_2 to greenhouses. Currently it is providing approximately 400 kton CO_2/yr to approximately 580 growers with a total greenhouse area of 1900 hectares (see Fig. 2). The system gives a net reduction in carbon emissions because the greenhouses would otherwise burn natural gas to produce at least some of that CO_2, rather than accepting lower crop growth. OCAP estimates the net carbon saving is about 200 kton CO_2/yr through the avoided natural gas use. OCAP gets its CO_2 from the Shell Pernis refinery and since 2010 the Abengoa bioethanol plant.

Fig. 2. OCAP pipeline (in green) with possible extensions (in blue).

The CO_2 demand of the greenhouses has a highly seasonal character, with much higher demand in the summer than in winter. This seasonal variation is due to two factors:

- In winter, the greenhouse owners use small gas-fired CHP (Combined Heat and Power) units to provide heat, electricity (for lighting) and CO_2 for the greenhouses, selling on the surplus electricity produced. In summer, there is less need to heat the greenhouses, so the owners prefer to turn off the CHP units and purchase the CO_2 from OCAP.
- In summer, more sunlight and the long daylight hours lead to stronger plant growth and higher CO_2 demand to further accelerate growth.

Currently, the OCAP system is supply-limited, they cannot expand because their supply of CO_2 is only just sufficient to meet the existing peak summer demand. There are more greenhouses that could be connected to the system if more CO_2 were available.

ROAD and OCAP (with support from the Port Authority and Shell) have therefore investigated the possibility to connect the two infrastructures and thereby create a CO_2 hub in Rotterdam. This would give CO_2 delivery to additional greenhouses (displacing natural gas emissions) and give the opportunity to store surplus CO_2 in winter which is currently being emitted.

1.3. Connecting CCS and CCUS in Rotterdam

By connecting ROAD to the OCAP pipeline (near one of their sources Abengoa, grey line in the Fig. 3) with a 20 km pipeline ROAD could provide CO_2 during peak demand in the summer, while the current CO_2 suppliers have the opportunity to transport and store their CO_2 in winter time when CO_2 demand from the greenhouses is low.

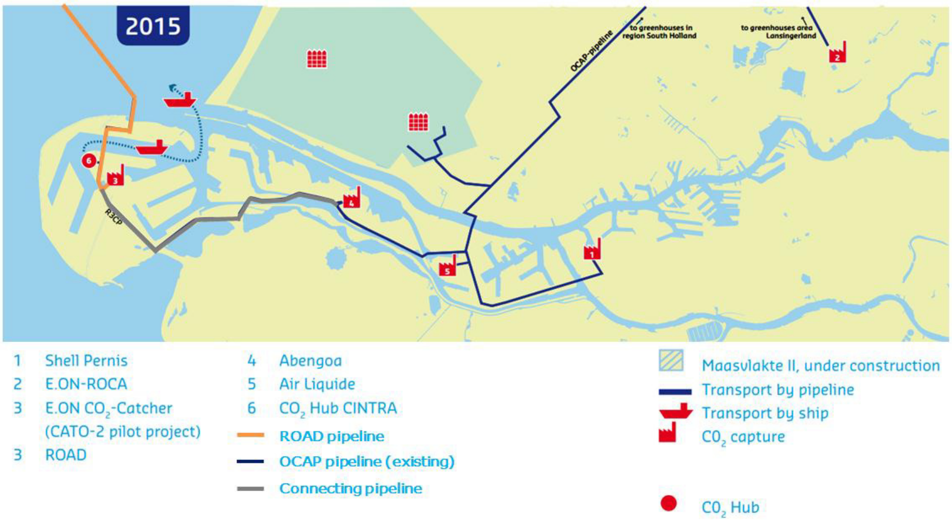

Fig. 3. Overview of CO_2 network in Rotterdam region (blue/OCAP is existing, gray is connection pipeline, and orange is new offshore pipeline to CO_2 storage site linked to ROAD project).

Although the distance between the CO_2 capture plant and the OCAP system is only approximately 20 km., the different pipeline diameter and operating regimes of the two systems provides an interesting challenge when looking into connecting them. This article will start off with a description of the design constraints both physical, i.e. the pipeline diameter, and the operating constraints. Thereafter the options to connect the two pipelines are described. In the following chapter a three step approach is used to make a selection of the most suitable/feasible connection is described.

2. Current design and operational regimes ROAD and OCAP

The CCS and CCU systems are designed and used differently. When the two systems are to be connected these design and operational parameters need to be taken into account. The new to build CO_2 pipeline from ROAD has the following specifications:

- Pipeline material: carbon steel (insulated)
- Diameter: 16 inch
- Distance: 5 km onshore, 20km offshore
- Capacity: 1.5 million tonnes/year (gas phase) and 5 million tonnes/year (dense phase)
- Design pressure: 140 bar
- Design temperature: -10 to 80 °C

Steady state operation based on only the ROAD capture plant will be in the operating envelope between 80-90 bar and 40-80 degree C. The pressure and temperature is controlled by ROAD to achieve the desired flow into the offshore reservoir, and these are changed according to reservoir pressure and availability of CO_2 from the power plant [1]. If additional third party (cold) CO_2 is going to be transported it has to meet the operating pressure and temperature or the effects of adding cold CO_2 to the warm pipeline need to be (further) investigated. The risk is that cooling the CO_2 will cause two-phase flow. The CO_2 flow from ROAD will vary between 18 and 47 kg/s, or 65 and 169 t/hr depending on the capture rate.

The OCAP pipeline is 26” in diameter and operates at between 7 - 21 bar on peak days. At these days, the CO_2 sources providing the CO_2 will deliver continuously. Because there is high demand during daylight, the pressure in the pipeline drops, while at night with low/no CO_2 demand the pipeline pressure rises, the pipeline buffer being used to store CO_2 for the following day. The restriction to 21 bar is based on the existing pipeline operating permit.

3. Options reviewed to connect ROAD to OCAP

Three diameters were considered for the new connecting pipeline:

- 16” to match the ROAD pipeline design
- 20” an in-between size
- 24” to approximately match the OCAP pipeline size (26” is an odd size. 24” is the nearest industry standard size)

The operating envelopes gave three operating pressures to review:

- 21 bar(g), based on the current operating pressure of OCAP
- 40 bar, assuming the OCAP pipeline can be recertified and re-permitted
- 90 bar, based on the operating pressure of ROAD

The different operating envelopes require some addition equipment to be installed to either supply OCAP or be able to store CO_2. Fig. 4 considers the 21 bar case and shows the additional compressor needed to enable CO_2 from the suppliers to OCAP to be stored.

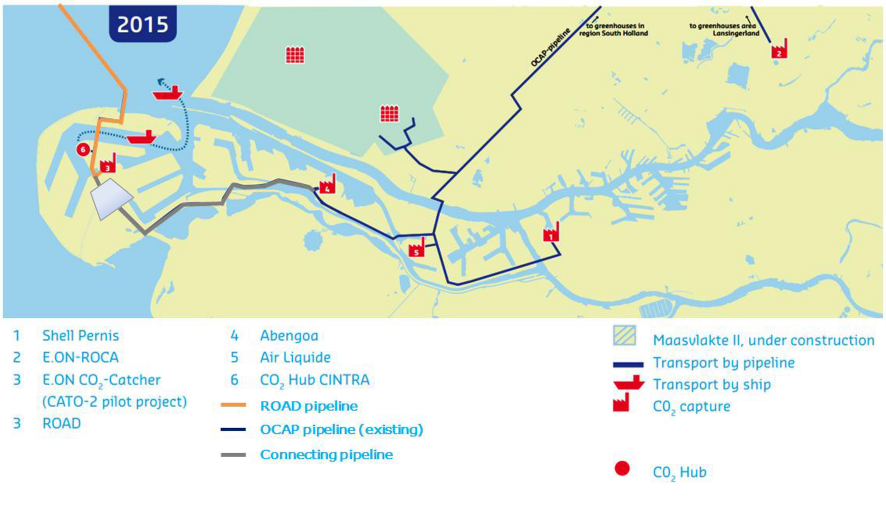

Fig. 4. Additional equipment needed to enable CO_2 storage if the connecting pipeline is operating at 21 bar.

Fig. 5 considers the 90 bar case and shows that an additional compressor and evaporator are required. The compressor is necessary to boost the 7-21 bar CO_2 supplied to the 90 bar needed for CO_2 storage. The evaporator is needed to heat the CO_2 flowing from ROAD to OCAP, otherwise Joule Thomson cooling when the CO_2 pressure is dropped from the ROAD pressure (80-90 bar) to the OCAP pressure (7-21 bar) will result in subzero temperatures and two-phase flow.

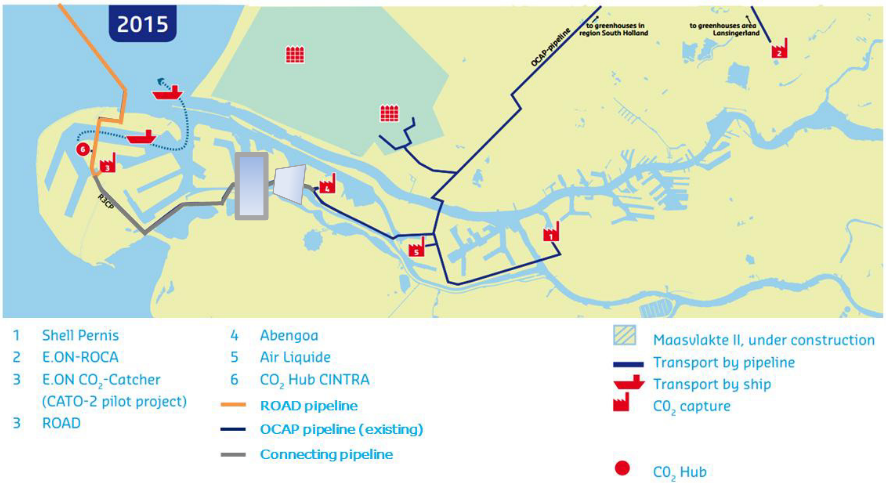

Fig. 5. Additional equipment needed to enable CO_2 supply and storage if the connecting pipeline is operating at 90 bar.

4. Option selection methodology

To come to the most feasible solution the review will be done according to the following steps:

- Step 1: Best feasible options based on pressure constrains and maximum throughput (flow) for different pipeline diameters
- Step 2: Preliminary cost estimate for the connection pipeline and associated system(s) for the different pipeline diameters
- Step 3: The softer factors for the different pipeline diameters

In some of the steps some combinations of pipeline size and operating pressure will drop out because they do not meet the design constraints.

5. Step 1: Pressure and flow review

In the first step the pipeline size will be reviewed taking into account the required arrival pressure at either the OCAP pipeline or the ROAD pipeline. For each pipeline design the arrival pressure will be reviewed to see whether the arrival pressure can be met. This will be done for the following two cases:

- 21 bar (operating pressure of OCAP system)
- 90 bar (max operating pressure of the ROAD system)

5.1. 21 bar case: flow from ROAD to OCAP

In this case ROAD will deliver the full CO_2 flow (169 t/hr) at peak demand periods (around summer). The arrival pressure at the OCAP pipeline needs to be 21 bar. ROAD will extract the CO_2 after the dehydration unit at 23.7 bar. Table 1 shows the arrival pressure given different pipeline diameters transporting the full flow of CO_2 from ROAD to OCAP. As shown, in order to deliver the full flow from ROAD (169 t/hr) to OCAP arriving at OCAP (near

Abengoa) at 21 bar a 20” pipeline would be sufficient. The 16” pipeline would not be sufficient, while a bigger diameter would do as well.

Table 1. Arrival pressure at OCAP dependent on pipeline size.

Pipeline size (inch)	Flow (t/hr)	Pout ROAD (Bar)	Pin OCAP at Abengoa (Bar)
16”	169	23.7	< 21
20”	169	23.7	21.2
24”	169	23.7	22.7

5.2. 21 bar case: flow from OCAP to ROAD

If OCAP suppliers (and future suppliers) would deliver their CO_2 (during winter) to ROAD the arrival pressure does not really matter, because additional compression would be needed (see Figure 12) to boost the pressure to 90 bar (and 40 to 80 degrees). However a small fraction (estimated 15 t/hr) could be compressed with the ROAD compressor if it arrives at 18 bar.

The current suppliers (including some future growth) deliver approximately 162 t/hr. The different pipeline sizes are reviewed to see at what pressure the CO_2 would arrive at the ROAD site given a certain pipeline size. The start point is CO_2 leaving the Shell site at 22 bar. Table 2 shows a 20” pipeline would be sufficient.

Table 2. Arrival pressure at ROAD dependent on pipeline size.

Pipeline size (inch)	Flow (t/hr)	Pout OCAP at Shell (Bar)	Pin ROAD (Bar)
16”	162	22.0	9.1
20”	162	22.0	17.9
24”	162	22.0	19.7

5.3. 90 bar case: flow from ROAD to OCAP

In this case ROAD will deliver the full CO_2 flow (169 t/hr) at peak demand periods (around summer). The departure pressure at the ROAD site is 90 bar. Dependent on the pipeline size the arrival pressure at the OCAP pipeline (near Abengoa) varies. The arrival pressure is however not critical, but is input to calculate the buffer capacity in the connection pipeline and evaporator to let the CO_2 down from the arrival pressure to 21 bar (see Fig. 5).

Table 3. Arrival pressure at OCAP dependent on pipeline size.

Pipeline size (inch)	Flow (t/hr)	Pout ROAD (Bar)	Pin OCAP at Abengoa (Bar)
10”	169	90	80
12”	169	90	86
16” and above	169	90	89-90

5.4. 90 bar case: flow from OCAP to ROAD

To allow CO_2 from the current suppliers to OCAP to flow to ROAD at 90 bar additional (central) compression is needed (see Fig. 5). The impact of the pipeline size is assumed to be equal as described in the case above (see Table 3) The ROAD pipeline / T&S system is however temperature controlled, but the CO_2 arriving from Abengoa is cold (assumed 10°C), unless the onshore pipeline is insulated as well. Further review is needed on the effects of "cold" CO_2 on the operation of the ROAD T&S system.

5.5. Preliminary selection based on best technical fit

From a technical point of view the following three options will be taken forward for further review (steps 2 and 3).

The first option is the 16" pipeline operating at 90 bar. The maximum flow is more than sufficient for flow either way. However, if ROAD is not running, (lack of) temperature control needs to be reviewed if other parties wish to store their CO_2. Also, OCAP needs to heat (evaporate) CO_2 from ROAD at the Abengoa site before it can be transported in their pipeline. In principle, this option has the highest buffer storage capacity, but two phase flow and low temperatures will occur when the pipeline pressure drops. Therefore it is not clear that this buffer capacity is usable in practice.

The second option is the 20" pipeline operating at 21 bar. The transport capacity (227 t/hr) would be sufficient for growth plans for CCS. The arrival pressure at the ROAD site of 14 bar requires additional compression if CO_2 will be transported and stored. The ROAD compressor can be used to compress 18 t/hr additional to the ROAD volume if the arrival pressure is not too low. This option has limited storage capacity for OCAP (estimated at 2 hours).

The third option is the 24" pipeline operating at 21 bar. This option has the similar advantages as the 20" 21 bar operated one, but has a higher maximum throughput capacity of 387 t/hr. It also has a bit higher storage buffer of approximately 3 hours for OCAP.

6. Step 2: high level cost estimate

In the first step three pipelines are selected as technical most feasible. In this step a cost estimate is made to highlight differences in cost and possibly reduce the selection further. Based on an in-house confidential cost estimating tool, with an accuracy of +/- 25%, the cost (CAPEX) of the pipelines is estimated assuming and including:

- 4 mm design allowance
- Horizontal Directional Drilling (HDD)
- 25% contingency

The additional equipment (including the evaporator and compressor, any additional piping on the ROAD site, and modifications to the ROAD plant) is not included in the cost estimate. The cost of the pipelines is estimated at:

- 16" 90 bar: 21 M€
- 20" 21 bar: 20 M€
- 24" 21 bar: 22 M€

The differences are very small. This is mainly due to the fact that the bulk of the cost for a pipeline is the civil works which is needed. The additional steel or a bigger HDD are not distinguishing factors between these options. Based on these small differences there is not a preference for one of the options. However, the 21 bar pipelines would only require adjustment to the ROAD compressor, which is still in the (detailed) design phase. The 90 bar pipeline however needs a more expensive heater. Although the cost of this equipment and these changes are not estimated they will be part of the qualitative comparison in the next step.

7. Step 3: other factors

After a first review of the design criteria three options (16” 90 bar, 20” 21 bar and 24” 21 bar) remained and the cost of these options was estimated. The cost proved not to be a distinguishing factor.

There are however other criteria which can to be taken into account to weigh the options. The following criteria will be looked into:

- Overall best value for money. This is ranked based on four sub criteria, being (i) Initial investment in the pipeline (CAPEX as estimated in step 2), (ii) Initial OPEX, (iii) Investment in a later stage, i.e. if other suppliers of CO_2 want to transport and store their CO_2, and (iii) Flexibility, meaning the buffer capacity of the connection pipeline
- Permitability. In this case permitting a 21 bar CO_2 pipeline is not a concern, as the OCAP pipeline sets a precedent for the local authorities. However a dense phase (90 bar) CO_2 pipeline has not been permitted before in the industrial hub of Rotterdam, or indeed in any comparable location in Europe. While in principle this should not be a barrier to permitting, the lack of reference experience combined with the high density of high value industry in the area might create local concern. Therefore a 21 bar pipeline has lower permitting risk.
- Fit with local and national ambitions, like the RCI/CCS vision, Deltaplan and Green Deal. RCI/CCS vision as explained in the introduction describes a big role for CCS in Rotterdam to reduce its CO_2 emissions. The Deltaplan currently being developed by the Port of Rotterdam reviews which infrastructure and extensions thereof are needed to bring steam, heat and CO_2 from the suppliers to the customers. Green Deal is an agreement to see if residual heat from the harbor area can be (re-)used in greenhouses. However, if external heat is supplied to greenhouses there also is additional CO_2 demand. Currently greenhouses produce their own heat with CHPs and use the CO_2 which is emitted during this process.
- Second life possibilities, i.e. the possibility to re-use the connecting pipeline for other purposes if CCS will not take off and ROAD will stop operation at some time

Table 4 gives a qualitative score on the different criteria for the different options.

Table 4. Ranking of the remaining options based on other factors.

		16” 90 bar	20”21 bar	24” 21 bar
Best value for money				
	Initial investment	21 M€ + heater	20 M€ + adjustment ROAD compressor	22 M€ + adjustment ROAD compressor
	Initial OPEX	-	+	+
	Flexibility (i.e. buffer capacity)	Highest, but difficult to realize	Lowest	Moderate
Permitability		-	+	+
Fit with local and national ambitions		+	-	0
Second life possibilities		+	0	-

8. Conclusion

A 20” or 24” pipeline operated at 21 bar seems to be the best option. Between these two pipelines the only distinction is the throughput (and therefore fit with ambitions of CCS and CCU). With a marginal additional investment the throughput increases by 50-60% between a 20” and 24” pipeline. Another advantage of using a 21 bar pipeline to connect the system is the possibility to control the temperature in the ROAD pipeline to the storage site.

Acknowledgements

The ROAD project is co-financed by the Government of the Netherlands and the European Commission within the framework of the European Energy Programme for Recovery (EEPR). In addition, the Global CCS Institute is knowledge sharing partner of ROAD and has given financial support to the project.

References

[1] Uilenreef J, Kombrink M. Flow assurance & control philosophy: Rotterdam Opslag en Afvang Demonstratieproject. Special report for the Global Carbon Capture and Storage Institute, http://decarboni.se/sites/default/files/publications/114746/road-project-flow-assurance-and-control-philosophy.pdf