Integration of Capture Plant and Power Plant

Rotterdam Opslag en Afvang Demonstratieproject

Special Report for the Global Carbon Capture and Storage Institute

Maasvlakte CCS Project C.V.

Date : 19 December 2013

Version : Final
# Table of Contents

Management Introduction and Summary........................................................................................................1

1. Introduction ................................................................................................................................................3

2. Project Factsheet .........................................................................................................................................4
  2.1 Project overview ....................................................................................................................................4
  2.2 Facts & figures .........................................................................................................................................4
  2.3 Planning ................................................................................................................................................6

3. Integrated CCS Chain of ROAD ................................................................................................................7
  3.1 Selection of post combustion capture technology .............................................................................7
  3.2 CCS development phases ....................................................................................................................8
  3.3 Integrated CCS chain of ROAD ...........................................................................................................9
    3.3.1 Capture ..........................................................................................................................................10
    3.3.2 CO₂ Compression ...........................................................................................................................11
    3.3.3 Transport .......................................................................................................................................11
    3.3.4 Storage ..........................................................................................................................................11
    3.3.5 Integration of capture plant and power plant ............................................................................12

4. ROAD Integration of Capture Plant and Power Plant ...............................................................................15
  4.1 Introduction ..........................................................................................................................................15
  4.2 Specific considerations to being ‘capture ready’ ................................................................................15
  4.3 Utility requirements of capture plant and impact on power plant ....................................................15
  4.4 Site lay-out ...........................................................................................................................................16
  4.5 Flue gas ................................................................................................................................................16
    4.5.1 Flue gas tie-ins ...............................................................................................................................18
  4.6 Steam and condensate ..........................................................................................................................22
    4.6.1 Low pressure steam ......................................................................................................................22
    4.6.2 Intermediate steam for reclaimer of capture plant ....................................................................27
    4.6.3 Condensate for cooling ..................................................................................................................27
    4.6.4 Power loss MPP3 ............................................................................................................................29
  4.7 Electrical power ......................................................................................................................................29
  4.8 Cooling water ........................................................................................................................................31
  4.9 Demineralised water ............................................................................................................................36
  4.10 Waste water .........................................................................................................................................37
    4.10.1 DCC condensate ..........................................................................................................................37
    4.10.2 Blow down from the deep FGD ....................................................................................................37
    4.10.3 Other waste water streams .........................................................................................................37
    4.10.4 Condensate from stack MPP3 ....................................................................................................38
  4.11 Controls hardware .................................................................................................................................38
  4.12 Other utilities .......................................................................................................................................38
  4.13 Flexibility of capture plant ....................................................................................................................39
  4.14 Control philosophy .............................................................................................................................40
    4.14.1 Control room and control hardware ............................................................................................40
    4.14.2 Start-up/shutdown procedures interfaces ....................................................................................41
4.14.3 Operating windows ........................................................................................................42
4.15 Specific emission levels ....................................................................................................42
4.16 Pollution control systems..................................................................................................43

5. Lessons Learned for Future CCS Projects ........................................................................45
# Table of Figures

- **Figure 1:** Location of ROAD CCS chain: Rotterdam port and North Sea ................................................. 4
- **Figure 2:** 3D visualization of MPP3 ........................................................................................................... 5
- **Figure 3:** Integrated CCS chain of ROAD ............................................................................................ 9
- **Figure 4:** Location of capture unit: Maasvlakte Power Plant 3 (view from south, 2013) ....................... 10
- **Figure 5:** Footprint available for capture plant on MPP3 (view from north, 2009) .......................... 10
- **Figure 6:** Summary of interactions between capture plant and MPP3 host .......................................... 12
- **Figure 7:** Block diagram integrated chain (MMP3, capture plant, transport and storage) ............. 13
- **Figure 8:** Technical design (Fluor) of 250 MWe equivalent post combustion capture plant ............... 16
- **Figure 9:** Position of flue gas tie-ins MPP3 .......................................................................................... 17
- **Figure 10:** Flue gas specification at inlet to capture plant ................................................................. 17
- **Figure 11:** Flue gas specification at exit from capture plant ............................................................. 18
- **Figure 12:** Maasvlakte Unit 3 CCS Demonstration Physical Flow Model ........................................ 19
- **Figure 13:** Overview flue gas ducts of MPP3 (from top of FGD till top of stack) .............................. 20
- **Figure 14:** Flue gas tie-in within stack of MPP3 .................................................................................. 21
- **Figure 15:** Flue gas tie-in; view from outside and from inside stack (during installation) ............. 21
- **Figure 16:** Simplified scheme of steam extraction system ............................................................... 24
- **Figure 17:** PFD of steam and condensate integration ..................................................................... 25
- **Figure 18:** Part view of the steam and condensate pipe routing at MPP3 ............................................. 26
- **Figure 19:** View of the low pressure tie-in T-piece being mounted (April 2013) ............................... 26
- **Figure 20:** View of medium pressure tie-in T-piece being mounted (January 2013) ....................... 27
- **Figure 21:** Conceptual scheme of waste heat integration applied in ROAD .................................... 28
- **Figure 22:** Simplified electrical diagram of MPP3 and connection to capture plant ....................... 30
- **Figure 23:** Cooling water intake MPP3 from harbor upper left, discharge in pond lower right ...... 31
- **Figure 24:** Cross-cut of cooling water supply channel ..................................................................... 33
- **Figure 25:** Top view of cooling water supply channel and connection to booster pump ............ 34
- **Figure 26:** Cross-cut of cooling water supply channel and connection to booster pump .......... 35
- **Figure 27:** Operating window capture plant ....................................................................................... 42
- **Figure 28:** CO₂ emissions of ROAD and/or biomass ......................................................................... 43
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bara</td>
<td>bar absolute</td>
</tr>
<tr>
<td>barg</td>
<td>bar gauge</td>
</tr>
<tr>
<td>cm</td>
<td>centimetre</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditures</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DCC</td>
<td>Direct Contact Cooler</td>
</tr>
<tr>
<td>EEPR</td>
<td>European Energy Programme for Recovery</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue Gas Desulphurization</td>
</tr>
<tr>
<td>FID</td>
<td>Final Investment Decision</td>
</tr>
<tr>
<td>Global CCS Institute</td>
<td>Global Carbon Capture and Storage Institute (the Institute)</td>
</tr>
<tr>
<td>GRP</td>
<td>Glass Reinforced Plastic</td>
</tr>
<tr>
<td>ha</td>
<td>Hectare (100 metre by 100 metre)</td>
</tr>
<tr>
<td>HAZOP</td>
<td>HAZard and OPerability</td>
</tr>
<tr>
<td>km</td>
<td>kilometre</td>
</tr>
<tr>
<td>LP</td>
<td>Low Pressure</td>
</tr>
<tr>
<td>MCP</td>
<td>Maasvlakte CCS Project C.V.</td>
</tr>
<tr>
<td>m</td>
<td>metre</td>
</tr>
<tr>
<td>mm</td>
<td>millimetre</td>
</tr>
<tr>
<td>MP</td>
<td>Medium Pressure</td>
</tr>
<tr>
<td>MPP3</td>
<td>Maasvlakte Power Plant 3</td>
</tr>
<tr>
<td>Mt</td>
<td>megatonne</td>
</tr>
<tr>
<td>Mt/a</td>
<td>megatonne per annum</td>
</tr>
<tr>
<td>MWe</td>
<td>megawatt electrical</td>
</tr>
<tr>
<td>Nm$^3$/hr</td>
<td>Normal Metres Cubed per Hour</td>
</tr>
<tr>
<td>OCC</td>
<td>overhead CO$_2$ condenser</td>
</tr>
<tr>
<td>ppmv</td>
<td>parts per million by volume</td>
</tr>
<tr>
<td>RCI</td>
<td>Rotterdam Climate Initiative</td>
</tr>
<tr>
<td>ROAD</td>
<td>Rotterdam Opslag en Afvang Demonstratieproject</td>
</tr>
<tr>
<td>t/h</td>
<td>ton per hour</td>
</tr>
</tbody>
</table>
Management Introduction and Summary

This report focuses on the integration of the existing coal-fired 1 070 MW Unit 3 of Maasvlakte Power Plant (MPP3) with the proposed new 250 MW scale carbon capture plant of the Rotterdam Opslag en Afvang Demonstratieproject (ROAD). Carbon capture technology has been the subject of considerable research to reduce the costs of Carbon Capture and Storage (CCS), and the subject of many publications. However, the integration with the main power plant also has important impacts on the efficiency and operability of the CCS chain, and is a significant project cost in its own right.

Published information from other large-scale post-combustion capture projects linked to power plants shows the range of challenges faced and the range of possible solutions. Each project so far is unique in at least some aspects. For example:

- The Kingsnorth FEED published by E.ON considered a new-build power plant, and assumed a modified steam turbine / feed heater train in the power plant to supply steam to the capture plant most efficiently. The electrical system was also fully integrated, with the capture plant compressor supplied off the power plant generator transformers.

- Scottish Power’s Longannet FEED considered a retrofit to an older existing unit, in which substantial modifications to the existing steam system were considered impractical. A new gas-fired CHP unit was foreseen to supply both steam and electricity to the new capture plant.

- At Sask Power’s Boundary Dam project, the only such project under construction, the existing steam system has been modified to supply the new capture unit, in this case as part of a major unit refurbishment. The opportunity was also taken to combine sulphur capture and carbon capture in a single combined retrofit.

This special report has been drafted by ROAD for the Global CCS Institute and describes how the power plant integration is achieved by ROAD. As with the above projects, ROAD also has unique features. It is a retrofit onto a very modern high efficiency unit (with unabated efficiency above 46% on a Lower Heating Value basis). The capture plant takes a slip stream of just under a quarter of the flue gas from the unit, making the impact on the host unit proportionally much smaller than in the other examples above, which is particularly important for the steam and cooling water interfaces.

Each of the interfaces is described in turn. Major design choices are explained, and the solutions adopted described in some detail. Some solutions are highly innovative, others more conventional. Among the highlights are the following:

- MPP3 has a wet stack, so there is no gas-gas heater after the Flue Gas Desulphurization (FGD). This means that the flue gas slip stream can be extracted anywhere between the FGD and the top of the stack. ROAD has chosen to extract and return the flue gas within the stack itself, allowing the weight of the new connections to hang off the stack. This gave civil engineering cost savings and kept the site layout compact.

- The supply of steam from the Medium Pressure (MP)/Low Pressure (LP) crossover (just before the steam enters the low pressure turbines) is conventional. However,
this pressure is insufficient for the capture plant when MPP3 is at part-load, particularly as ROAD would like to maintain the capture plant at full-load in this scenario. ROAD proposes a steam jet booster (also called a steam ejector) powered by MP steam to boost the steam supply to the original full-load pressure – a configuration ROAD believes to be completely novel in a carbon capture application. This allows accurate control of the steam pressure at all loads of MPP3 down to 40%.

- Although a retrofit, ROAD does include further heat integration. Heat in the CO\textsubscript{2} at the stripper outlet is used to warm MPP3 boiler feed water, both improving cycle efficiency and reducing the cooling load of the capture plant. The reduction in cooling load is of particular value for ROAD, as the cooling water (seawater from the Rotterdam harbour) is a slip stream taken from the MPP3 supply and is therefore limited. Cooling water taken by ROAD reduces the supply to MPP3 and thus also has an impact on MPP3 unit efficiency.

- The largest source of waste water from capture plant is from the direct contact cooler, and is simply water condensed from the MPP3 flue gas. As such, it is of quality suitable for re-use in the MPP3 FGD unit. This means that the addition of carbon capture substantially reduces the sweet water consumption of MPP3.

While future CCS projects will have their own unique challenges, and not all the lessons from ROAD will be transferrable, it is hoped that the ideas and experience presented in this special report will enable project engineers to better integrate and optimise capture units and power plants in the next generation of projects.
1. Introduction

ROAD is the Rotterdam Opslag and Afvang Demonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the first large-scale, integrated Carbon Capture and Storage (CCS) demonstration projects on power generation in the world. The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain on power generation.

ROAD is initiated by E.ON Benelux N.V. and GDF SUEZ Energie Nederland N.V. They have set up a joint venture Maasvlakte CCS Project C.V. to realize this CCS demonstration project. The ROAD capture plant, located next to the Maasvlakte Power Plant 3 (MPP3), will have a capacity of 250 MWe equivalent. ROAD is to demonstrate the feasibility of the full CCS process chain at an industrial scale and to show that it can be adapted to the requirements of a coal-fired power plant. The technology selected for the capture plant is ‘post combustion’. The specific capture process will be based on capture with amine based solvents, amino-acid salt solvents or ammonium. The captured CO₂ will be transported by GDF SUEZ E&P Nederland B.V. to an offshore gas field of TAQA Energie B.V. by a 25 km pipeline from the capture plant to the gas field for permanent storage.

Based on the tender for the European Energy Programme for Recovery (EEPR, July 2009), ROAD started in 2010 with the engineering of the integration of the capture plant with MPP3. The MPP3 design was more or less fixed, and was already under construction, though some subsystems still required detailed engineering. ROAD investigated how an efficient integration could take place; minimizing energy and life time costs and taking into consideration the constraints caused by space limitations, avoiding delays in construction of MPP3, permitting and technical limitations. While the demonstration period of the project should last for five years, the life-time of the technical design was based on 20 years. Whether the operation will be continued after the demonstration period will to a large extend depend on the economical parameters that are expected at that time. A high sufficient CO₂ price should be in place to cover all operational and maintenance costs to run the capture plant without external funding.

Previous to this special report, the ROAD project published special reports for the Global CCS Institute on:
- Lessons learnt.
- Handling and allocation of business risks.
- Project execution strategy.
- Stakeholder management.
- Permitting process.
- Mitigating project risks.
- Non-confidential FEED study.
- CO₂ technology selection methodology.
- Flow Assurance & Control Philosophy.

The main focus of this special report is on the integration of the capture plant with MPP3 rather than on the capture plant itself. The main integration issues are described in chapter 4 and include: flue gas tie-ins, steam supply, electric power supply and cooling water, and some smaller connections.
2. Project Factsheet

2.1 Project overview

ROAD is the Rotterdam Opslag and Afvang Demonstratie project (Rotterdam Capture and Storage Demonstration Project) and is one of the first large-scale, integrated Carbon Capture and Storage (CCS) demonstration projects on power generation in the world.

ROAD is a joint project initiated by E.ON Benelux N.V. and GDF SUEZ Energie Nederland N.V. Together they constitute the limited partnership Maasvlakte CCS Project C.V. The intended partners of ROAD are GDF SUEZ E&P Nederland B.V. for the CO₂ transport and TAQA Energy B.V. for the CO₂ injection and permanent storage. 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.

2.2 Facts & figures

ROAD applies post combustion technology to capture the CO₂ from the flue gases of a new 1100 MWe coal-fired power plant (Maasvlakte Power Plant 3) located in the Rotterdam port and industrial area. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 million tonnes of CO₂ per year. The capture plant is planned to be operational in 2017.

ROAD plans to store the captured CO₂ in a depleted gas reservoir under the seabed of the North Sea. These gas reservoirs are located in block sector P18 (P18-6, P18-4 and P18-2) of the Dutch continental shelf, 20 km off the coast. The depleted gas reservoirs are at a depth of 3.5 km under the seabed of the North Sea. The CO₂ will be injected from the platform into depleted gas reservoirs. The estimated storage capacity is 35 Mt.

Figure 1: Location of ROAD CCS chain: Rotterdam port and North Sea
Base installation: E.ON Maasvlakte Power Plant 3 (Rotterdam, The Netherlands)

- Output: 1 070 MWe, single train unit (e.g. one boiler, one steam turbine-generator set)
- Combustion process: Pulverised coal boiler
- Fuel: Hard coal blends from different countries all over the world
- Efficiency: 46%
- Operational: 2013
- Capture ready

Capture Plant

- Technology: Post combustion
- Technology provider: Fluor
- Capacity: 250 MWe equivalent (23.4% of flue gas from MPP3 is treated)
- Capture rate: 90%
- CO₂ captured: ~ 1.1 Mt/a
- Operational: 2017

Transport

- Insulated pipeline
- Diameter: 16 inch
- Distance: 5 km onshore, 20 km offshore
- Capacity: Gas phase: 1.5 Mt/a

Figure 2: 3D visualization of MPP3
(equivalent to 5 Mt/a in dense phase)

- **Design specifications**: Pressure 140 bar
  Temperature 80°C

### Storage
- **Depleted gas reservoir**: P18-4
- **Operator**: TAQA
- **Depth**: 3.5 km
- **Estimated capacity**: ~ 8 Mt (for P18-4 only)
- **Available**: 2014

#### 2.3 Planning

The high level schedule of the ROAD project is as follows:

- **14 July 2009**: Application submitted for funding under European Energy Programme for Recovery
- **September 2009**: Project selected for funding by European Commission
- **May 2010**: Ministerial order Dutch funding published
  - Grant Agreement signed by European Commission and ROAD Project
- **September 2010**: Front-End Engineering Design studies Capture Plant completed
  - Starting note Environmental Impact Assessment published
- **June 2011**: Submitting Environmental Impact Assessment, permit applications
- **May 2012**: Capture permits definitive and irrevocable
- **September 2013**: Storage permits definitive and irrevocable
- **Q3/Q4 2013**: Final Investment Decision
- **2017**: Start of operation CCS chain
- **2017-2020**: Demonstration phase CCS chain
3. **Integrated CCS Chain of ROAD**

This chapter describes what developments influenced the design of the ROAD project and how the integrated chain of the project reached its present form including the interfacing between MPP3 and capture unit.

3.1 **Selection of post combustion capture technology**

The most developed post combustion capture processes rely on chemical scrubbing using alkaline solvents with high capture capacity for the CO₂, e.g. amines, amino salts or ammonia. Post combustion capture processes usually work with an aqueous solvent solution that undergoes a cyclic absorption/desorption process. The CO₂ from the flue gas is absorbed by the solvent in a so-called “absorber” column and subsequently desorbed from the loaded solvent in a so-called “stripper” column, generating a highly concentrated CO₂ flow. The absorption process is exothermic and thus, cooling is required to achieve good performance. The endothermic stripping process causes the main energy demand of the whole capture process as heat is required to extract the CO₂ from the liquid phase in the solvent.

Activities of E.ON and GDF SUEZ in this field of technology include an ambitious pilot plant fleet that is described in section 3.2, and collaborative R&D in post combustion capture within European Framework Projects including CASTOR, CESAR and OCTAVIUS. Furthermore, E.ON is participating in CAPRICE and has a membership of the leading international 'club-funded' R&D programs of the University of Texas at Austin and the International Test Center, University of Regina, and further funding of various research activities at universities; GDF SUEZ is also participating in ACACCIA aiming at cost reduction of capture processes using chemical solvents and the development of new physical-chemistry breakthrough processes.

E.ON and GDF SUEZ selected for this CCS project at MPP3 the post combustion capture technology with chemical scrubbing for the following reasons:

- Construction activities for MPP3 had already started at the moment the decision concerning the CO₂ capture technique was made. Post combustion is the only realistic CO₂ capture technique (retrofitting) since pre combustion and oxy-fuel combustion are not applicable to the MPP3 layout.

- Post combustion capture via chemical scrubbing is considered to be the most developed form of technology (lowest technical risk) to demonstrate carbon capture on industrial scale.

- Technology suppliers for chemical scrubbing processes are considered to be more mature than other technology suppliers, providing more substantial process warranties currently, as the technology has already been demonstrated, albeit on a smaller scale.

- At the moment, numerous ultra-modern pulverized coal fired power plants are being built or planned worldwide, amongst others by E.ON and by GDF SUEZ. Post combustion capture technology lends itself more to retrofit scenarios compared to the other CCS technologies and could be vital for the future operation of such power plants as the CO₂ emission price may rise significantly.
3.2 CCS development phases

A cornerstone of R&D effort is the ability to pave the way for promising technologies to be tested on industrial scale. This implies the following phased approach for the further development of post-combustion capture technology. In the process of developing CCS to industrial scale by 2020, two phases are differentiated:

1. ‘Phase I’ is to test the practical feasibility of capture processes with real flue gases from coal-fired power plants and to improve the efficiency of those processes. This can only be tested at reasonable costs with small scale pilot plants in the range of up to 10 MW which use innovative solvents and incorporate innovative designs of various components. Therefore, E.ON and GDF SUEZ have worked together with international partners such as Alstom, Hitachi Power Europe, Siemens, Cansolv, Mitsubishi, Fluor and TNO. Within the Dutch CATO program for example, E.ON has hosted the power plant site (Maasvlakte) for the TNO pilot plant, which has already been operating on real flue gas from MPP1/2 for more than 3,000 test hours (more information at www.co2-cato.nl) and continues to do so. This pilot plant has been designed for applying an amino acid salt (developed by TNO) as a solvent. In May 2009, a pilot plant by Alstom began operation E.ON’s power plant Karlshamn (Sweden). This plant was designed for applying ammonia as a solvent, using the ‘chilled ammonia process’. A Siemens pilot plant has been in operation at E.ON’s power plant Staudinger (Germany) for several years. This pilot plant has been designed for applying an advanced process with amino acid salt (developed by Siemens) as a solvent. Furthermore, E.ON’s largest pilot plant at its Wilhelmshaven (Germany) power plant has now been operational for more than one year and serves to study Fluor technology directly relevant to the ROAD capture plant.

2. ‘Phase II’ is to successfully demonstrate the complete CCS chain on an industrial scale, to show that it can be adapted to the requirements of a coal fired power plant and to prove that it can be operated in a safe way. Among others, Phase II focuses on the integration of the capture plant into the power plant, the understanding and the optimization of the interactions between the single components within the CCS chain (power plant, capture plant, transportation and storage). Demonstration plants in the range of several 100 MW are additionally able to reflect on integration concerns and the interactions between the single components of the CCS chain.

The capture plant at the site in Maasvlakte would fit well into the development strategy of E.ON and GDF SUEZ, as it is a valuable intermediate step between pilot plant and full-scale commercial deployment of CCS.
3.3 Integrated CCS chain of ROAD

ROAD is one of the first large-scale, integrated CCS demonstration projects on power generation in the world. The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain on power generation. In the power industry, to date, CCS has primarily been applied in small-scale test facilities. Large-scale demonstration projects are needed to show that CCS is an efficient and effective CO$_2$ abatement technology within the next 5 to 10 years.

![Integrated CCS chain of ROAD](image)

**Figure 3: Integrated CCS chain of ROAD**

MPP3 is currently (late 2013) in the latter stages commissioning and features state-of-the-art supercritical steam conditions and best available technology for emission reduction. With thermal efficiency above 46% and carbon emissions at 755 g CO$_2$/kWh before capture, it already has world leading environmental performance. Biomass co-firing is planned to further reduce emissions.
ROAD’s capture unit is closely integrated with the power plant, with tie-ins for steam, various water streams (cooling, demin, fire, drinking and waste water), electricity, telecommunications and control systems as well as the flue gas connection. These systems are carefully optimised. Key tie-ins for flue gas and steam are already installed so that the capture unit can be constructed, connected and commissioned without requiring a long outage of the power plant.

3.3.1 Capture

ROAD applies post combustion technology to capture the CO$_2$ from the flue gases of a modern supercritical 1070 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the Rotterdam port and industrial area. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 Mt of CO$_2$ per year.
The capture process used will be Fluor’s Econamine FG+ process, which was selected after a thorough competitive tendering process including two competitive FEED studies. It is one of the best proven technologies available for post-combustion capture, and has been licensed to 28 industrial plants in a range of applications.

Flue gas from the MPP3 chimney is cooled, further cleaned to remove all sulphur, and then passed into an “absorber” vessel where 90% of the CO₂ is captured using an amine solvent. The remaining flue gas (mostly inert nitrogen gas) is returned to the chimney. The CO₂ is removed from the solvent in the “stripper” vessel. Heating the solvent using steam from the power plant causes the CO₂ and the solvent to separate. This “regenerated” solvent can then be re-used to capture more CO₂, while the CO₂ released is cooled and passed to the compression system.

3.3.2 CO₂ Compression

Compression and drying takes place within the capture unit to allow cost effective integration of electrical, cooling water and control systems. The CO₂ is compressed using an integrally geared multi-stage compressor. Interstage cooling gives high efficiency and progressive water removal, with a drying unit (using molecular sieve technology) installed at about 20 bar to achieve the dryness required for transport. A final CO₂ cooler after the compressor discharge gives control of CO₂ temperature entering the transport pipe in the range of 40-80°C. This CO₂ stream will be more than 99.9% pure with <50 ppmv of water and can be at pressures of up to 129 bara.

3.3.3 Transport

The transport system of ROAD consists of a 16 inch insulated pipeline from the E.ON site to the P18-A platform of TAQA in the North Sea at about 25 km from the Maasvlakte in Rotterdam. From the capture unit the CO₂ will be compressed and transported through a pipeline: 5 km over land and 20 km across the seabed to the P18-A platform. The pipeline has a planned transport capacity of 1.5 Mt of gaseous CO₂ per year (equivalent to 5 Mt CO₂ per year in dense phase). It is designed for a pressure of 140 barg and a temperature of 80°C.

3.3.4 Storage

ROAD will store the captured CO₂ in P18-4. This reservoir block contains only one well, the P18-4/A2 well. The existing P18-4/A2 gas production well will be converted into an integrated injection-monitoring well. In principle, the P18-4 reservoir has been classified as suitable for CO₂ storage providing a stable long-term containment (EC opinion, 2012). These conclusions are essentially based on the knowledge of the reservoir obtained during exploration and production of the fields, the low pressure in the reservoir being brought back to the most stable situation of hydrostatic pressure after ending the CO₂ injection, the sealing capacity of the cap rock and the fact that natural gas has been contained in these reservoirs for millions of years.
3.3.5 Integration of capture plant and power plant

There is a range of interactions between the capture plant and the host power plant, MPP3, as illustrated schematically in the figure below.

![Figure 6: Summary of interactions between capture plant and MPP3 host](image)

The integration of the power plant, capture, transport and storage is novel to the EU. The only existing reference is the Boundary Dam project in Canada which is smaller (roughly 100 MW scale) and uses different capture and storage technologies (Boundary Dam storage is in an onshore EOR field with test-scale aquifer injection in addition, whereas ROAD uses an offshore depleted gas field). The integration of the capture plant with the power plant, compression, pipeline and depleted gas field storage is therefore a first-of-a-kind. The ROAD design includes no intermediate storage (other than that provided by pipeline line pack) so the whole chain will operate as a single integrated system.

In addition, the capture plant process is subject to on-going continuous improvement by Fluor, supported by pilot studies involving the parent companies of the project sponsor. The plant design will therefore include a number of optimizations and improvements not seen in existing small-scale units. These include:

- Heat integration whereby the warm CO₂ at the stripper outlet is used to provide feed water heating for the power plant.
- A steam ejector is used to control the pressure of the steam from the power plant, allowing continued efficient operation of the capture plant when the power plant is at part load.
- Vacuum flash condenser and intermediate absorber cooling for in the solvent cycle to optimize the process performance (minimizing the energy required).
- Use of the latest packing designs and washing / scrubbing designs for optimum thermal and environmental performance.
Figure 7: Block diagram integrated chain (MMP3, capture plant, transport and storage)
In the block diagram above the main installations, transport and storage blocks are shown, as well as the integration of the capture plant with MPP3:

- the flue gas path (only a 23.4% slip stream of the flue gasses of MPP3 at full load is treated in the capture plant);
- the steam/condensate systems;
- the high voltage electrical systems;
- the sea water cooling system;
- the demineralized water supply;
- the process water supply.
4. **ROAD Integration of Capture Plant and Power Plant**

4.1 **Introduction**

This chapter describes the integration of the several systems of the power plant and the capture plant in more detail with the most emphasis on the four large interfaces steam/condensate, flue gas, cooling water and electrical system.

4.2 **Specific considerations to being ‘capture ready’**

The design of the capture plant integration is done by E.ON New Build & Technology BV. The coal-fired unit MPP3 started construction a several years ago and therefore the integration of the capture plant is a retrofit. MPP3 is certified as “capture ready” because of the ability to install post combustion full scale CO\textsubscript{2} capture in terms of space and resources (e.g. plot area, cooling water, utilities, steam turbine design, CO\textsubscript{2} storage site).

MPP3 received its capture-ready certificate based on TÜV NORD Climate Change Standard TN-CC 006. The standard contains requirements in particular regarding the technological and site-specific (e.g. cooling water, utilities, steam turbine design) feasibility of retrofitting a full-size post-combustion carbon capture system at the power plant location, the availability of the space which will be needed for the capture plant, the possibility of transporting CO\textsubscript{2} from the power plant site to a CO\textsubscript{2} storage site and the possible effects on plant safety and environment. The TÜV certificate was granted on 19 May 2009.

The extension of the capture plant from the 250 MWe equivalent ROAD scale to the full MPP3 unit would require an additional 800 MWe equivalent capture unit (or a new full scale unit) with other solutions for the utilities and integration. These are not described in this report.

4.3 **Utility requirements of capture plant and impact on power plant**

For post combustion capture implementation at a coal fired power plant the following streams needs to be integrated:

- flue gas extraction from the main flue gas duct at the bottom of the stack;
- return of treated flue gas from the capture plant to main power plant stack;
- low pressure steam extraction from the steam turbine for the capture plant's reboiler;
- return of steam condensate from the capture plant's reboiler into the steam cycle;
- cooling water for capture plant's coolers from main cooling system inlet;
- cold condensate from pre-heater train to the capture plant coolers for waste heat recovery;
- heated condensate return to the pre-heater train;
- electric power supply to capture plants via power plant's auxiliary system;
- control systems;
- several smaller utilities (e.g. de-mineralized water).
4.4 Site lay-out

The capture installation will be built on the plot space next to the stack of MPP3. Because the MPP3 installation was designed and already under construction at the start of the project, the plot space has some challenges for the capture installation compared to a greenfield situation. While most of the site is unconstrained in height, there are zones with height limitation due to coal transport conveyor belts. Underground cooling water piping and buried 10.5 kV cables also cross the site and cause further constraints. Pipe racks on the Maasvlakte site have a passage height of 5 m and at some areas of 8 m.

The supplier has developed a design of the capture and compression installation to fit all the restrictions. Figure below shows a 3D picture of the resultant design. The total area available for this demonstration is circa 1.2 ha.

![Diagram of the capture installation](image)

Figure 8: Technical design (Fluor) of 250 MWe equivalent post combustion capture plant

4.5 Flue gas

The capture plant was designed for an equivalent electrical output of 250 MW and will therefore only need to treat a portion of the flue gas produced by MPP3. In design conditions, the capture plant needs to treat 23.4% of the flue gas from the FGD of MPP3. The flue gas slip stream has a volume flow of approximately 698 000 Nm³/hr at 48°C, which was considered as the maximum volume flow to the capture plant.
A significant portion of the MPP3 flue gas will be extracted and routed to the capture plant. The flue gas will be extracted downstream of the FGD unit of MPP3. The FGD is downstream of the DeNOx installation and the Electrostatic Precipitator (ESP).

![Diagram showing the positions of flue gas tie-ins MPP3](image)

**Figure 9: Position of flue gas tie-ins MPP3**

In the DeNOx approximately 90% reduction of NOx is achieved by injecting ammonia (NH3) in the flue gas upstream of a catalytic converter. In the ESP around 99.95% of the fly ash and dust in the flue gas is removed.

Since MPP3 is a new unit, all of its environmental systems have deployed the Best Available Technology (BAT) for emission reduction. Taken in combination with the high baseline efficiency of the plant (due to its supercritical steam cycle) these represent very attractive conditions under which to prove post-combustion capture, which is known to be sensitive to acid gas components and to require a significant energy input.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas Volume Flow (STP, wet) from MPP3 (after FGD)</td>
<td>m³/hr</td>
<td>3 006 580</td>
</tr>
<tr>
<td>Flue Gas Volume Flow (STP, wet) to CC Plant</td>
<td>m³/hr</td>
<td>700 000</td>
</tr>
<tr>
<td>Flue Gas Temperature</td>
<td>°C</td>
<td>48.2</td>
</tr>
<tr>
<td>Flue Gas Gauge Pressure at FDG Outlet</td>
<td>mbar</td>
<td>+ 2.0</td>
</tr>
</tbody>
</table>

**Composition (wet)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Vol.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>11.2</td>
</tr>
<tr>
<td>CO₂</td>
<td>13.7</td>
</tr>
<tr>
<td>N₂</td>
<td>70.9</td>
</tr>
<tr>
<td>O₂</td>
<td>3.4</td>
</tr>
</tbody>
</table>

*STP = Standard Temperature and Pressure at 0°C and 1.01325 bar*

**Figure 10: Flue gas specification at inlet to capture plant**
Parameter | Unit | Value
--- | --- | ---
Flue Gas Temperature | °C | 34.9
Flue Gas Gauge Pressure at FDG Outlet | mbar | + 2.0
Composition (wet)

<table>
<thead>
<tr>
<th>Component</th>
<th>Vol.-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>5.7</td>
</tr>
<tr>
<td>CO₂</td>
<td>1.7</td>
</tr>
<tr>
<td>N₂</td>
<td>87.4</td>
</tr>
<tr>
<td>O₂</td>
<td>4.2</td>
</tr>
</tbody>
</table>

*STP = Standard Temperature and Pressure at 0°C and 1.01325 bar*

Figure 11: Flue gas specification at exit from capture plant

4.5.1 Flue gas tie-ins

MPP3 has a wet stack with no gas-gas heater. This means that the flue gas extraction and return can be anywhere after the FGD (normally must be between the FGD and gas-gas heater).

Three positions were evaluated to extract the flue gas from MPP3 to the capture plant:

1. On top of the FGD of MPP3
2. In the horizontal Glass Reinforced Plastic (GRP) duct from the FGD to the stack of MPP3
3. Inside the stack of MPP3 where the GRP duct turns upwards.

The position inside the stack was chosen to avoid changes the original plot plan of MPP3 and to minimize supporting structures and scaffolding for the ducting from the tie-in points to the capture plant. The stack can be used to support the new tie-in structures and an obstacle free routing downwards is available inside the concrete stack.

The discharge of the treated flue gas, which has a volume flow of approximately 566,000 Nm³/hr at 35°C will be routed back to the wet stack of MPP3.

Two other discharge options (discharge via stack on top of the CO₂ Absorber or via a dedicated stack) were considered, but appeared to be not feasible due to NOx dispersion and permitting reasons. Therefore returning the flue gas to the MPP3 stack was the only option.

During the engineering of the flue gas tie-ins a combined Physical Flow Model (PFM) study and Computational Fluid Dynamic (CFD) study on the modified stack were performed in 2010.

The objectives of the physical model study were to: evaluate the effect of adding the new CCS supply and return ductwork and gas flows on the existing liquid collection system for
the condensate that is formed in the wet stack; design an effective liquid collection system for the new configuration; and evaluate the effect of the CCS on temperature distributions within the stack. To that end, an already existing 14.69:1 scaled physical flow model was modified with the proposed CCS ducting arrangement and evaluated.

The proposed system was evaluated over three flow conditions corresponding to No CCS, Full Load with CCS, and Partial Load with CCS.

Conclusions were drawn that the existing liquid collection system performance was acceptable at the new flow conditions. The studies confirmed that no flue gas recirculation occurs between return and extraction tie-in and there is only a very minor impact on the pressure drop within this section (the impact is less than 1 mbar additional pressure drop caused by the nozzles when the capture plant is retrofitted but not in operation).

Figure 12: Maasvlakte Unit 3 CCS Demonstration Physical Flow Model
The above mentioned flow studies resulted in the detailed design of the two tie-ins and nozzles in the stack of MPP3. Inside the stack, the flue gas duct has a 90° turn. At this location, two nozzles have already been installed that extend into this 90° turn (see figure above). The nozzles will facilitate the connection of the power plant to the capture plant (and the subsequent return of the treated gas) without the need for an extended outage of the power plant. They are capped until final connection to the capture plant will take place.

In combination with similar tie-ins already made to the steam cycle of MPP3, to allow rapid connections to be made to a capture plant, these installations represent (it is believed) a unique investment in a power plant to facilitate the retrofit of carbon capture technology.
Figure 14: Flue gas tie-in within stack of MPP3

Figure 15: Flue gas tie-in; view from outside and from inside stack (during installation)
4.6 Steam and condensate

The operation of the capture plant requires steam [no exact steam parameters can be mentioned due to IP rights] at two pressure levels:

1. Low pressure (LP) steam is required to supply the reboiler of the desorber column
2. Intermediate pressure (IP) steam for reclaimer operation that is used intermittently to maintain solvent quality by removing heat stable salts and degradation products from the solvent. The amount of the IP steam is less than 1% of the LP steam.

Condensate from above mentioned steam deliveries are returned to the MPP3 plant. Furthermore, condensate from the steam cycle is used for cooling purposes in the capture plant.

4.6.1 Low pressure steam

Low pressure steam is required to supply heat to the reboiler of the desorber column in the capture plant at a temperature range between 120-140°C. Due to the large heat duty of the reboiler (>100 MWth) condensing low pressure steam is the most suitable solution to supply the necessary heat.

1. Low pressure steam can be supplied in multiple ways; the ones considered in ROAD are summarized below:
2. MPP3 with no CCS as reference;
3. MPP3 with CCS with the steam for the capture plant provided by an auxiliary steam boiler fired with oil or gas;
4. MPP3 with CCS with the steam provided for the capture plant by an auxiliary steam boiler fired with oil or gas and a backpressure steam turbine to generate the electrical power for the capture plant;
5. MPP3 with CCS with the steam provided for the capture plant by heat recovery steam behind a gas turbine coupled to a generator that provides electrical power for the capture plant and surplus power to the grid;
6. MPP3 with CCS with the steam provided for the capture plant by the existing steam cycle and power from the MPP3 10kV system;
7. MPP3 with CCS with the steam provided for the capture plant by the existing steam cycle with optimal heat integration and power from the MPP3 10kV system.
The table and graph below show the calculated total net power output and electrical efficiency under typical conditions with an auxiliary boiler efficiency of 90% and a gas turbine efficiency of 35%.

<table>
<thead>
<tr>
<th>Option</th>
<th>Total Power MWe</th>
<th>Electrical Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MPP3 no CCS</td>
<td>1 070</td>
<td>46.3%</td>
</tr>
<tr>
<td>2 MPP3 +AuxB+CCS</td>
<td>1 040</td>
<td>42.4%</td>
</tr>
<tr>
<td>3 MPP3 +AuxB+STT/GEN+CCS</td>
<td>1 070</td>
<td>43.0%</td>
</tr>
<tr>
<td>4 MPP3 +GT+HRSG+CCS</td>
<td>1 091</td>
<td>43.7%</td>
</tr>
<tr>
<td>5 MPP3+CCS</td>
<td>1 010</td>
<td>43.7%</td>
</tr>
<tr>
<td>6 MPP3+CCS+heat integration</td>
<td>1 012</td>
<td>43.8%</td>
</tr>
</tbody>
</table>

The options 2, 3 and 4 demand high capital cost, also they introduce additional functional systems and increasing complexity in the layout and the operation of the power plant, without giving advantages on the overall process efficiency. Those options showed a higher total power output through the introduction of additional fuel input, but no better overall efficiency than the steam extraction options from MPP3.

According to the integration philosophy of minimizing the modifications at the power plant, only the options with low pressure steam extraction from the MPP3 steam system have been considered further.
At full load of MPP3, low pressure steam can be extracted directly from a branch of the steam pipe that supplies the fifth pre-heater with low pressure steam derived after the Medium Pressure (MP) turbine. The figure underneath illustrates the steam extraction system. This line branch has been originally designed to supply heaters of a district heating systems but at the moment is not yet employed for that purpose.

![Figure 16: Simplified scheme of steam extraction system](image)

When MPP3 is operating in full load, the steam that is used in the desorber (stripper) of the capture plant will be extracted from the steam turbine downstream of the medium pressure turbine at a pressure of 2-4 bar. At part load of MPP3 this pressure is not high enough and another (higher pressure) extraction point will have to provide the steam.

Design of this extraction system is of high importance because of the high operational costs involved. Three options were evaluated to have increased steam pressure in part load:

1. Modification of the crossover pipe MP to LP turbine and installing valves to keep enough pressure during part load.

2. Extraction from a higher pressure source (leading to low part load efficiency of MPP3).

3. Installing a steam jet booster to increase the pressure extracted from the main extraction point (more complex and extra investments).

Option 1 was initially investigated with the manufacturer of the steam turbine of MPP3 but abandoned because of the high investments, operational risks and long outage of MPP3 for the modification.

For option 2 the only suitable extraction point is the cold reheat. However, in some part load situations of MPP3 the amount of steam that can be extracted is not high enough and would require part load of the capture plant as well. Also the electrical losses are high because of the high quality steam that is used. Furthermore, the disadvantage of this option is the shifting of the steam extraction to the cold reheat during operation that is rather challenging.
Option 3 was found the most economical. The high pressure steam for the steam jet booster will be extracted from the cold reheat steam pipes of MPP3. A view of the integrated process flows for the steam and condensate of MPP3 and the capture plant (brown dashed box) is shown in the figure below.

![Figure 17: PFD of steam and condensate integration](image)

Budget quotes and projected performance have been received for the projected solution of the steam jet booster. This solution is not worked out in all details yet, however risks are limited if the steam jet booster does not function as projected. The risk is limited because MPP3 is not expecting to operate for long periods at part load, and the reheat steam can still provide some steam if necessary.

The approx. 1 200 mm steam line will be routed on a 450 m long dedicated pipe bridge together with other piping required for the utilities of the capture plant. A routing was found, but detailing is on hold until FID. This option was chosen instead of enlarging a parallel MPP3 pipe bridge that would have disturbed the design and construction process too much. The condensate from the steam will be pumped back to the condensate system of MPP3 via the same pipe bridge.
Tie-in pieces for the extraction of the LP steam and the cold reheat have already been constructed during the construction of MPP3 and before the FID of the ROAD project (see pictures below). Execution after commercial operation would have taken a long outage and therefore caused high costs.
4.6.2 Intermediate steam for reclaimer of capture plant

Intermediate pressure (IP) steam is used for the reclaimer operation. As a result of the Value Engineering after the FEED phase a decision was made to use IP-steam instead of electrical heaters. This small stream can be extracted from the auxiliary steam header of MPP3 or from the MP steam supply to the steam jet booster. A 50 mm steam line is planned using the same pipe bridge as the LP steam and condensate pipes.

4.6.3 Condensate for cooling

Waste heat from the capture plant can be integrated in the condensate preheating train, aiming at increasing overall plant efficiency. The capture plant includes several coolers where waste heat is released to cooling water, thus dissipated into the environment. Condensate at low temperature can be used instead of cooling water, recovering heat for pre-heating the condensate leaving the main condenser.

In the capture plant the following heat exchangers are potential sources for waste heat integration:

- direct contact cooler: it cools the water stream used to quench the inlet flue gas upstream the absorber;
- lean solvent cooler: cools the lean solvent before entering the absorption column;
- washer coolers: cool the solvent/water streams of the washing loops at the top of the absorber;
- overhead CO2 condenser (OCC): cools the wet CO2 before compression at the top of the stripper;

- CO2 compressor intercoolers: cool the CO2 between sequential compression stages.

In practice, waste heat integration occurs when a portion of condensate exiting the main condenser is used in the capture plant coolers instead of flowing through the normal pre-heater path. This has the effect of reducing the heat duty of LP preheaters, improving the power output at the generator and thus the plant efficiency. The portion of the condensate flowing in the coolers is proportional to the heat duty of the cooler.

Depending on the final temperature reached by the condensate inside the cooler it will be re-introduced in the pre-heaters train at a point where the condensate has a similar temperature. The higher the temperature achieved inside the coolers the larger the efficiency benefit.

![Conceptual scheme of waste heat integration applied in ROAD](image)

**Figure 21: Conceptual scheme of waste heat integration applied in ROAD**

On the CO2 side of the OCC the inlet and outlet temperature are 89°C and 40°C, respectively. This means that the full heat load of the condenser (28.8 MWth) can be used for condensate pre-heating. The condensate will be supplied at 19 bar(a) and 26°C as it exits from the main ST condenser; it will be returned at 16-18 bar(a) and a temperature in the range of 70-80°C and added to the main stream of condensate after the 3rd preheater where the temperature is approximately 90°C. With respect to overall plant efficiency with capture, the integration gives an increase in efficiency of approximately 0.2% points.

This waste heat integration is chosen because the higher revenues associated with the increased power output largely compensate the higher investment cost required. Another important reason that influenced this decision is the reduction of the cooling water requirement for the capture plant. In fact, by integrating the OCC no more cooling water is required for that cooler with significant savings in the total cooling water flow for the capture plant. It is estimated that 3 000 m³/h less cooling water will be used, accounting for about 20% of total capture plant cooling water. Therefore, the extra investment required in the waste heat integration is not only compensated by higher revenues but also by the reduced investment for the capture plant's cooling water system.
The selected method for the heat integration has also been evaluated in cooperation with KEMA and presented at the 2012 Power-Gen conference in Cologne (see: Integration of the 250 MWe demo post-combustion CO₂ capture plant at MPP3, ROAD/DNV KEMA, 2012).

4.6.4  Power loss MPP3

Calculations have been made by E.ON of the impact on MPP3 power output of the steam and condensate flows mentioned in the previous chapters, and also including the impacts of changes to MPP3 pump power consumption and the changes in steam flow and cooling water flow on the MPP3 condenser performance. The conclusion is that at full-load of MPP3, the full impact of these changes is a reduction in net electricity generation of MPP3 of 28.1 MW. This is in addition to the electrical load of the capture plant itself, discussed below. At part load of MPP3 (below about 90% load) it rises substantially, due to the increased use of MP steam for the steam jet booster. At 70% load of MPP3 it is calculated at 39.0 MWe, and 39.3 MWe at 40% load. Generally MPP3 will operate at full-load, however, in the financial modelling an average power loss of MPP3 of 58.0 MWe (including the electrical load of the capture plant) has been used to take into account periods of part-load operation of MPP3.

4.7  Electrical power

For the maximal approximately 30 MW electrical power supply for the capture plant a 10kV connection with the MPP3 plant is foreseen. About half of this supply is needed for the CO₂ compressor. Normally the auxiliary 10 kV system of MPP3 is energized through the auxiliary transformers powered by the generator of MPP3 or the 380 kV step-up connection. In emergency situations the 10 kV system of MPP3 can also be supplied from a 150 kV grid connection.

The electrical power for the capture plant will be provided via a 10 kV switchgear that will be installed at the control building of the MPP3 power plant and which is linked to the 150/10 kV transformer that is connected to the external 150 kV grid.

Since the supply to the MPP3 10kV system from the external 150 kV grid is required only in emergency cases (e.g. operating failures of auxiliary power transformers), the capture plant can be supplied with electrical energy via the external grid transformer.

This solution gives the lowest CAPEX because no extra transformer or high voltage grid connection is needed and the expected availability of electrical supply for the capture plant is high enough. Disadvantages are the extra grid costs because electrical power cannot be supplied directly from MPP3. However, considering the limited number of operating hours of the CCS demo, this is outweighed by the lower CAPEX.

The current CCS system design will supply the CCS system with two 10kV parts, each with eight or nine switchboards.

The average electrical power consumption, combined with the reduced output of MPP3 of 28-39 MW, leads to forecast average total power consumption on average of 58 MW.

Under the agreements with E.ON, this is charged by E.ON to the ROAD project at cost, this being calculated from the wholesale electricity on the day. This is because it is either electricity E.ON is unable to sell due to the CCS plant operation (for the case of lost
production from MPP3) or has to buy off the grid (for the case of capture plant electrical power consumption).

Figure 22: Simplified electrical diagram of MPP3 and connection to capture plant
4.8 Cooling water

MPP3 uses sea water for cooling. The cooling water is pumped out of the harbour and runs under the capture plant through a channel to the MPP3 unit. The heated cooling water is discharged via a cooling water pond on the other side of the power plant into another part of the harbour:

![Cooling water intake MPP3 from harbor upper left, discharge in pond lower right](image)
During the conceptual design of the integration three options were evaluated to connect the capture plant to this cooling water (CW) system:

**CW-option 1**

![Diagram](Image)

**CW-option 2**

![Diagram](Image)

**CW-option 3**

![Diagram](Image)

For the three options a cycle model was developed to calculate the efficiency losses of the integration of the capture plant with MPP3.

Option 2 has the advantage of short cooling water connections, but compared with option 1 the efficiency loss of MPP3 was 0.11% worse because of the warmer cooling water for MPP3.

Option 3 makes use of waste heat of the capture plant to heat condensate of MPP3, resulting in a calculated efficiency gain of 0.12% compared with option 1. Furthermore this option has the advantage of a reduced sea water cooling system for the capture plant. After economical calculations that showed the feasibility, this option was selected.

The three existing sea water cooling pumps of the main cooling system of MPP3 have enough capacity to provide cooling for MPP3 and the capture plant. When the capture plant is in operation the steam extracted for the desorber (stripper) is not discharged in the main condenser of MPP3, so cooling water demand is shifted from MPP3 to the capture plant. For the capture plant one dedicated booster pump will be installed to extract the amount of sea water that is needed.
The cooling water channel crossing the capture plot is a rectangular concrete structure, consisting of two parallel square channels lying side by side, with a size of 2.55 m by 2.55 m. The channels are accessible for cleaning and inspection purposes. For this reason access hatches (manholes) are placed in the channels at regular intervals.

![Cross-cut of cooling water supply channel](image)

*Figure 24: Cross-cut of cooling water supply channel*

To supply up to 13 000 m³/h cooling (sea)water to the capture plant, it is foreseen to connect suction lines of the capture plant booster pump to both manholes (ID 800 mm) of an inspection well in the concrete cooling water channel between the main cooling water pumps and the machine house of MPP3.
The two manhole covers will be replaced with (flanged GRP) DN800 pipe spools running to a suction header, which feeds the capture plant cooling water booster pump. The DN800 spool pieces will be designed in such a way that they are removable, which will allow access to the manholes when this is needed.

Figure 25: Top view of cooling water supply channel and connection to booster pump
The concrete superstructure can be modified without operational consequences. The piping from the manholes to the capture plant can also be installed while MPP3 is in operation, with only the final connection to the manholes during the required stop of MPP3 for all final connections.

The cooling water from the capture plant will be discharged to the outlet pond through a new DN 1200 GRP pipe.
4.9 Demineralised water

Demineralised water is consumed in the capture plant for:

- Make-up wash water at the top of the absorber.
- Dilution of NaOH 50% to 20%.
- Make-up for closed cooling water system.
- Solvent filter flushing.
- Several other users.

In MPP3 two different qualities of demineralised water are available. The lower quality is coming in to MPP3 externally pre-demineralised from the local water company EVIDES via a DN 200 pipeline. This water is then further treated within MPP3 to produce boiler feed water qualities according to VGB R 450.

The EVIDES water quality is as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity</td>
<td>&lt; 0.2 µS/cm</td>
<td>&lt; 0.5 µS/cm</td>
</tr>
<tr>
<td>SiO₂</td>
<td>&lt; 25 ppb</td>
<td>&lt; 50 ppb</td>
</tr>
<tr>
<td>Fe</td>
<td>&lt; 20 ppb</td>
<td>&lt; 50 ppb</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt; 5 ppb</td>
<td>&lt; 50 ppb</td>
</tr>
<tr>
<td>TOC</td>
<td>&lt; 50 ppb</td>
<td>&lt; 100 ppb</td>
</tr>
<tr>
<td>Na</td>
<td>&lt; 5 ppb</td>
<td>&lt; 10 ppb</td>
</tr>
</tbody>
</table>

Temperature range: 3 to 30°C
Supply pressure: around 2-3 bara
Flow rate: max. 200 m³/h

The capture plant supplier has confirmed that the EVIDES water quality is sufficient for their purposes. Therefore it is intended to not to use the higher quality demineralised water, unless required for reasons other than quality.

Two pumps will be installed and a DN 80 transport line of around 250m will be constructed to transport up to 15 m³/h from the MPP3 demineralised water system to the capture plant.
4.10 Waste water

Most waste water is produced by the pre-scrubber section of the capture plant. The pre-scrubber combines a cooling section, the Direct Contact Cooler (DCC), and a desulphurization unit (the deep Flue Gas Desulphurization unit – deep FGD). Both sections produce waste water, but the two streams differ significantly in quantity and quality.

A table of waste and other water streams that are identified is listed below with the flow rates. The waste water streams are discussed individually in the sections below.

<table>
<thead>
<tr>
<th>Water flows to/from capture plant (under typical conditions)</th>
<th>m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP and IP condensate return</td>
<td>205</td>
</tr>
<tr>
<td>Condensate for cooling</td>
<td>562</td>
</tr>
<tr>
<td>Cooling water</td>
<td>12 290</td>
</tr>
<tr>
<td>Demin water</td>
<td>8</td>
</tr>
<tr>
<td>Condensate DCC</td>
<td>44</td>
</tr>
<tr>
<td>Potable water</td>
<td>1</td>
</tr>
<tr>
<td>Reclaimer effluent</td>
<td>-</td>
</tr>
<tr>
<td>Fire water</td>
<td>-</td>
</tr>
<tr>
<td>Sewage water</td>
<td>-</td>
</tr>
<tr>
<td>Storm water</td>
<td>-</td>
</tr>
</tbody>
</table>

4.10.1 DCC condensate

The DCC excess water stream amounts to 44 t/hr and consists of water condensed from the flue gas. This stream can be mixed with process water for feeding the FGD absorber of MPP3, thereby reducing the intake of fresh water from a nearby lake by more than a third. A DN100 transport line of around 250 m will be constructed to discharge this stream in process water tank of MPP3.

4.10.2 Blow down from the deep FGD

The SO₂ scrubbing loop uses a sodium hydroxide solution to remove further SO₂ from the flue gas before it enters the absorber. This is to minimise solvent consumption, as SO₂ chemically binds with the solvent forming a heat stable salt. The alkaline solution also scrubs some CO₂ resulting in the formation of sodium bicarbonate in addition to the sodium sulphate and sodium sulphite formed from the SO₂. The blow down from the DCC scrubbing loop is a relatively small waste stream, at 0.3 t/h, and the salts contained are common in the environment. Under the permit, this waste stream can be safely mixed with the cooling water used in the capture plant (flow rate 12 200 t/h) and discharged into the sea.

4.10.3 Other waste water streams

The Reclaimer effluent will be stored in the Reclaimer Waste Sump which is sized to hold 30 days of continuous Reclaimer operation effluent. The waste will be disposed of periodically via a third party waste disposal contractor. Storm water drains are returned to MPP3 and
integrated with the existing storm water collecting system, which is aimed to maximize utilization of rainwater as process water. Sewage water from the capture plant control room block is also connected to the MPP3 sewer.

4.10.4 Condensate from stack MPP3

The flue gas from the absorber of the capture plant returning to the stack of MPP3 can be contaminated with MEA. Part of this MEA can be absorbed by the condensate that is formed in the stack of MPP3. This condensate is normally reused in the FGD of MPP3. The expected amount of carryover of MEA to this condensate is less than 100 g/hr. Research work at the capture pilot project in Wilhelmshaven may deliver more accurate figures. As there is much uncertainty on these figures for the MPP3/ROAD situation, it is not appropriate to engineer mitigation measures in this phase of the project.

Possible mitigation measures if MEA contents in the condensate should be too high may include:

1. Dumping the condensate in the waste water installation of MPP3 or drain to the cooling water discharge and apply for additional permits for this way of discharging.
2. Collecting the condensate in a storage tank and transport it to a waste treatment.
3. Measures in the capture plant to minimize MEA carryover, e.g. second washing stage in absorber, aerosol removal, temperature control etc.

Costs for these measures, if required, will be borne by ROAD.

4.11 Controls hardware

The control of the capture plant shall be completely integrated with the control system of MPP3. The control system ABB 800xA allows the assignment of different control functions to the local control room or to the main control room of the power plant. Therefore there is complete flexibility over whether the capture plant and the interfaces of the plant with the power plant will be controlled from the main control room or if the control of different parts of the capture plant is assigned to the local control room. In any case, in each control room it will be possible to access and/or visualize all process data.

The integration will be done by using a redundant optical fibre cable between the main control system of the MPP3 power plant and the local control system in the capture plant.

4.12 Other utilities

- Telecom connections

- Fire water: The fire water systems of MPP3 and the capture plant will be completely integrated. The fire water pumps and lines of MPP3 and have enough capacity to facilitate the extra hydrants in the capture area and connections to fire water systems within the capture plant.

- Potable water: a connection with the MPP3 system is foreseen to supply the local control room and safety shower areas of the capture plant.
Instrument- and plant air will be provided by a dedicated package for the capture plant. No connections with the MPP3 air systems are foreseen.

4.13 Flexibility of capture plant

The base power plant for the capture chain, MPP3, will operate in a highly competitive power market. At times, when demand is low and when other generators are available to generate at lower cost, then the base power plant will not generate and the capture chain can obviously not operate. Under some other circumstances, when power is in scarce supply and the price of power is high, it may not make commercial sense to run the capture chain and the system would again be shut down.

Under such circumstances, the full chain must clearly be capable of a controlled shut-down and, of course, a controlled return to service after a shut-down which might be measured in hours or days.

MPP3 will generate at whatever load is dictated by short-term local market conditions which might be anywhere from its minimum stable generation to full load, or at any point in between. The capture plant is sized so that there is sufficient flue gas available to supply the full design flow of flue gas from MPP3 provided that it is generating at or above its minimum stable load. However, the steam flow available for regeneration in the capture plant becomes a constraint below around 40% of full load (i.e. around 430MWe) and the capture plant (and downstream systems) would have to ramp down below that load\(^1\).

Capture plant dynamics are not expected to be a limiting factor in the chain. Due to the innovative nature of the ROAD project, it is intended that some testing will be conducted to assess the dynamic behaviour and capabilities of the capture process. Studies to date indicate that the capture plant, which is fully automated, will be at least as flexible as the power plant to which it is attached, so this is not expected to be a problem. Further tests on this are planned for the E.ON / Fluor pilot at Wilhelmshaven. In any case, it is expected that for most of the time, the commercial drivers in place will lead to the capture plant being operated at or near its full capacity, where this is possible.

The nature of the power market dictates however that the ROAD solution for CO\(_2\) compression, pipeline transport, injection and storage must be capable of start-up and shut down and flow assurance during such transients has been an important element of the design work conducted to date.

The design specification for the capture plant was to be able to operate down to 40% load. In fact no major technical limit has been identified, and the capture plant can in principle sustain very low loadS. However, the compressor is not designed to provide low flows and would have to operate on recycle\(^2\). This makes low loads on the capture plant very energy

---

\(^1\) The following minimum ramp rates are defined for ramping operation: 40-60 % load: 3-4 % MCR/minute; 60-95 % load: 4-6 % MCR/minute. “MCR” shall be related to the flue gas flow at nominal load and design flue gas conditions, 1 % of MCR is equivalent to 7,000 m\(^3\)/h STP wet.

\(^2\) The compressor is optimised for maximum efficiency at CO\(_2\) full flow. Turndown is achieved through inlet guidevane control and 100% flow recycle loops around the “wet” and the “dry” sections. This gives full flexibility to operate at any load, but is relatively inefficient at CO\(_2\) flows below 70-80% of full load.
inefficient as most of the electricity load required at full-load is still required for low load operation. Therefore it is assumed that operation below 40% load will not be economically viable, and therefore will not occur except under test or transient (start-up or shutdown) conditions. Flow assurance assessment studies based on the minimum flow of 40%, maximum flow, start-up and shut-down conditions have been performed to ensure good operability.

4.14 Control philosophy

The capture plant will have an independent control system, coordinating all necessary operation and monitoring activities. The operation modes and transitions between these modes which are described below will be executed fully automatically with a minimum of operator actions required.

The capture plant will have the ability to operate in the following modes:

- Start-up capture Plant with MPP3 already in operation at any load (*).
- Ramping up and down capture plant and MPP3 in parallel at the same ramp rate (*).
- Ramping up and down capture plant and MPP3 in parallel at different ramp rates.
- Ramping up and down the capture plant leaving MPP3 in stable operation at any load.
- Stable operation capture plant with MPP3 ramping up and down (*)

The modes marked with (*) are expected to be used mostly. The capture plant shall be optimized for these modes, without restricting operation in the other modes mentioned.

Stable operation of the capture plant will be possible within 40-100% of the design range. The capture plant will automatically adjust itself to the selected target load. The target load can be a fixed operator selected value, or it can be a moving set point, e.g. the MPP3 boiler load. In the first case the capture plant will operate at constant load, independent from MPP3 operation. Otherwise it will follow the MPP3 boiler load and correspondingly treat a fixed percentage of flue gas. The balance of the main circulating system flow rates in the capture plant will automatically adjust by the “load following control”. The same applies for the flows of the utilities from MPP3 that are controlled by the control functions in the capture plant. To perform these controls, the Operator will manually choose one of the control modes.

4.14.1 Control room and control hardware

The control of the capture plant will be completely integrated in the control system of MPP3, although, initially at least, the CCS control will be conducted from a separate control room. The control system ABB 800xA allows the assignment of different control functions to the local control room or to the main control room of the power plant.

Fire and gas detection alarms of the capture plant and the MPP3 will be communicated to both alarm systems. The interface between these systems will be redundant and hard wired.
4.14.2 Start-up/shutdown procedures interfaces

Start-up Operation – Prior to the actual start of capture operation the capture plant shall perform all necessary preparations, such as pre-heating of pipes and equipment as required. This may take some hours depending on the length of the shut-down period. The preparations shall be performed fully automatically on operator request. Once the capture plant is ready for operation it shall wait for the start signal from the DCS. It shall then wait for the formal RELEASE, which reflects readiness of the MPP3 plant (signal from MPP3) and fulfilled minimum conditions on the interfaces between capture plant and MPP3 (to be monitored internally by capture plant). Having the RELEASE the capture plant shall automatically ramp up to the selected target load at its maximum speed.

Start-up procedures for all utilities are not yet defined in detail in this phase of the project; however some specific start-up issues are identified for the interfaces:

**Cooling water**: Start-up of the sea water cooling system of the capture plant is in the first phase of the start-up procedure. There may be a restriction for the amount of sea water extracted from the cooling water channels for the capture plant during start-up when MPP3 is (almost) at full load and requires almost all the available cooling water. Therefore the sea water cooling pump of the capture plant is restricted to 6 000 m$^3$/h during start-up until the capture plant begins drawing LP steam.

**Steam**: The 450m LP and IP steam line will have to be drained and heated up to superheated conditions.

**Condensate for cooling**: At start-up the transport pumps for the condensate of MPP will be switched-on, but the condensate will be circulated over the supply and return line until the return temperature at MPP3 reaches a minimum value. This will prevent mixing too cold condensate with the warm condensate stream after preheater #3 of MPP3 and reduces unnecessary power losses.

When all utilities are switched on and the main capture plant systems are ready, the flue gas dampers can be opened and the blower can be started to suck in flue gas from MPP3 to start capture of CO$_2$.

When the capture plant is expected to be shut down for a short period of time (i.e. less than 24 hours), the plant is brought to “standby” status mode in order to allow for a faster start-up to full production. The purpose of “standby” mode is to keep the capture plant in a ready state while drawing minimum steam and electrical power from MPP3. This is achieved by reducing the main circulating process pump flow rates to 40% of normal capacity (to be confirmed based on selected pump minimum flow requirements). Additionally, the sea water system flow rate shall be reduced to 6 000 m$^3$/h to prevent starving MPP3 vacuum condenser of sea water. Finally, the steam system will remain pressurized.

If the capture plant is to be shut down for a long period of time (more than 24 hours), then all of the rotating equipment shall be shutdown, the steam system shall be depressurized, and the solvent shall be allowed to cool. It should be noted that the 24 hours as a breakpoint between short term and long term shutdown is only a guideline. The capture plant can be kept in “standby” mode for longer, if desired.
### 4.14.3 Operating windows

Stable operation shall be possible in the following ranges:

- **Nominal load (MCR\(^3\))**: 100%
- **Flue gas flow at nominal load**: 700 000 m\(^3\)/h STP wet
- **Load range capture plant**: 40-100%
- **Flue gas flow over capture plant load range**: 280 000-700 000 m\(^3\)/h STP wet
- **Load range MPP3**: 25-100%

\(^3\) Maximum Continuous Rating

![Figure 27: Operating window capture plant](image)

MPP3 is expected to operate most of the time at or close to full load, however, this may change in the future when changes in power generation assets occur. To be able to run the capture plant at full load when MPP3 is in part load, the minimum load of MPP3 may have to be raised to obtain sufficient steam quantities and pressure for the steam supply to the capture plant. An important limiting parameter at MPP3 is the minimum flow through the boiler reheater.

### 4.15 Specific emission levels

When operated in design conditions, MPP3 will emit a flue gas stream of about 1 084 kg/s, containing approximately 15 Vol.-% (dry) CO\(_2\). The new-build plant will therefore produce approximately 755 gram CO\(_2\)/kWh, resulting in annual CO\(_2\) emissions of about 5.7 million tonnes. To lower the net specific CO\(_2\) emissions of the plant, E.ON Benelux may take the opportunity to co-firing biomass such as wood pellets. Currently, E.ON Benelux is studying the maximum rate of biomass that can be co-fired. Expectations are that co-firing of 20 wt-% biomass is realistic.
The graph below gives an impression of the effects on specific CO₂ emissions of both the capture plant and co-firing biomass. Also the combination of both measures to reduce CO₂ emissions is shown. Especially the specific part load emissions of MPP3 can be reduced substantially by keeping the capture plant at full load. The low emissions at part load of MPP3+ROAD are caused by the fact that in this situation a higher percentage of the CO₂ produced by MPP3 is captured when the capture plant stays at full load.

![Graph showing CO₂ emissions of MPP3 with ROAD and/or biomass](image)

**Figure 28: CO₂ emissions of ROAD and/or biomass**

The flue gas from the absorber is returned to the power plant stack and emitted to atmosphere with the remaining untreated flue gas from MPP3. This gas stream is predominantly nitrogen (87.4%) but also contains under design conditions 5.7% water, 4.2% oxygen, 1.7% CO₂ and 1% argon.

The permit for MPP3 has been modified to include the capture plant. Under this permit, the main emission limits relevant to the capture plant are on ammonia (5 mg/Nm³ limit) and total organic carbon as measured by a flame ionisation detector, where the permit limit is 23 mg/Nm³. Total organic carbon includes the amine and degradation products (expected to be principally acetaldehyde). The emissions guaranteed by Fluor are within those limits.

### 4.16 Pollution control systems

To prevent pollution of the MPP3 systems and to ensure that environmental permits are not violated, most connections that receive a flow from the capture plant to MPP3 are monitored online. In less critical connections sampling points are available. HAZOP (HAZard and OPerability) sessions were held to verify the present designs, but detailed engineering is not yet finished and additional HAZOP sessions on the interfaces may lead to additional monitoring equipment.

The flue gas return is equipped with an analyser that measures VOC, NH₃, SO₂ and NOₓ.
To ensure the quality of the steam condensate returned to MPP3, conductivity and pH are measured in the discharge of the Reboiler Condensate Pumps.

Condensate for cooling is not likely to be contaminated due to the fact that the pressure at of the condensate is always higher than the pressure at the gas side of the overhead CO\textsubscript{2} condensers. However sampling points are available to confirm this.

Emissions to the sea water side of the cooling system are prevented by applying partially an indirect cooling system with an intermediate fresh water cooling loop. The process streams that are directly cooled by sea water are equipped with plate and frame heat exchangers that will minimize the chance of leakage to the sea water side.

The capture plant equipment containing hazardous substances are placed on a paved area, surrounded by a bund wall. Potential spills will be prevented from seeping in the underground by the paving; storm water is collected in a sump where it can be monitored before pumping to the MPP3 storm water system.

Individual equipment drains are connected directly to dedicated sumps within the capture plant.
5. **Lessons Learned for Future CCS Projects**

The way the ROAD project is funded, with substantial capital grants, but a low reward for operation, created a strong incentive to minimise capital costs, with a much lower focus on reliability. Based on statistical component reliability data, the capture plant should deliver 95% availability (excluding planned maintenance). However, poor reliability will simply extend the operating period until the required level of CO₂ is captured to comply with the funding requirements. Since the power plant can operate independently of the CCS plant, the commercial impact of a loss of electricity generation from the power plant is completely avoided if ROAD is unreliable.

This had a high impact on some major design choices. The capture plant is single train (including a single compressor). For the interfaces with MPP3, capacity margins in the MPP3 design are used for the capture plant where possible they are available most of the time. For example, the spare pump and flow margin in the cooling water system are used to supply the capture plant cooling water. Thus if one of the cooling water pumps of MPP3 is out of service, for example, the choice can be made to reduce the load of MPP3 or reduce the load of the capture plant. Also, no margins are included to cover off-design operation of the power plant. The capture plant is simply designed to handle 250 MW – worth of flue gas at the MPP3 design conditions. For example, if the power plant is operating at lower efficiency for any reason, the flue gas volume created in generating 250 MW would increase. The capture plant is not designed to accommodate this increased flow – it is not necessary to deliver the technology demonstration goal of ROAD. Similarly, if cooling water temperatures are high in summer, carbon capture is likely to be restricted.

On the positive side, the treatment of only 23% of the flue gases of MPP3 in the capture plant created unique opportunities that would not have existed with a higher treatment percentage. Because of the relatively small capture plant size, the capture plant could make use of the MPP3’s electric auxiliary system, MPP3’s cooling water system, the extraction of steam from the existing steam cycle of MPP3. The steam extraction solution adopted at MPP3 is rather unique thanks to the existing spare steam extraction branch originally designed for district heating, which is not used at the moment for that purpose. This avoided the need for modifications of the crossover that are typically considered for additional steam extraction in existing coal power plants. Optimization of the efficiency – the heat integration by using MPP3 condensate for part of the cooling – has been considered and applied, limited to technical solutions that have shown a positive effect on the operational costs.

The opportunistic interface design approach led to relatively low investments (€30-35 mln.) for the utility interfaces of the ROAD project. This would not be achievable when all the flue gases have to be treated with the same capture rate.

Another consideration in the design of the interfaces was the fact that at the moment of engineering the capture plant and its interfaces, the MMP3 power plant was already under construction. Engineering the capture plant together with the power plant would have led to other solutions with lower CAPEX, e.g. more optimal lay-out and combining utility systems. Furthermore, agreement had to be reached on the design of the interfaces when the Final Investment Decision (FID) of the capture plant was not yet made. This also favoured solutions with minimal changes to the original MPP3 design. Only adaptions that would cost too much outage later on (and thereby outage costs) were executed before the
FID. This was only applicable on the construction of steam and flue gas interfaces, which would require more than 8 weeks after commercial operation date of MPP3, leading to considerable outage costs. Presently an outage of MPP3 of 2-3 weeks is foreseen for the final connections of all interfaces and may be executed during a regular maintenance outage.

A higher (say 40-100%) treatment of the flue gas of MPP3 would not have been possible with the present interface solutions. Steam, cooling water and electricity for the capture plant would require other sources – or significant modifications to MPP3 – leading to considerably higher investments. For a new power plant the experience from the design of the ROAD project would lead to the following recommendations for a highly integrated capture plant.

1. For the electrical supply the auxiliary electrical system of the power plant would have to be enlarged to feed the high power demands of the capture and compressor installations. To avoid a much larger auxiliary electrical system a directly steam driven compressor could be considered.

2. The sea cooling water system would have to be dimensioned larger (+20%) to supply the much higher cooling needs caused by the capture plant (if the same boiler size would be used).

3. For the steam supply several options would exist and would have to be economically evaluated with the starting points of the design. Full integration with the steam cycle of the power block would most likely mean major changes in the steam cycle compared with the present MPP3 design, for instance comprising a smaller LP steam turbine, possibly also with a throttle valve between MP and LP turbine to ensure enough pressure for the extraction to the carbon capture plant in part load of the power plant. For this case also a steam jet booster can be considered and/or more extraction points in the MP turbine.

4. Further heat integration is limited by the surplus of low grade waste heat in the capture plant and the limited amount of condensate available in the pre-heater train, but in principal this surplus could be used to feed district heat grids. Especially so called fourth generation district heating grids that use supply temperatures below 70°C and return temperatures lower than 30°C can be used to provide cooling for the carbon capture plant thereby reducing CO₂ emissions even further.

5. The almost pure condensate that is released in the Direct Contact Cooler (DCC) can be used as process water in the power unit almost eliminating external fresh water supplies.