LESSONS FROM THE ROAD PROJECT FOR FUTURE DEPLOYMENT OF CCS

GHGT-14, Melbourne, Session 1C
Large scale Integrated Projects - Experience

Andy Read, Chris Gittins, Jan Uilenreef, Tom Jonker, Filip Neele, Stefan Belfroid, Earl Goetheer &
Ton Wildenborg (presenter)

road CCS

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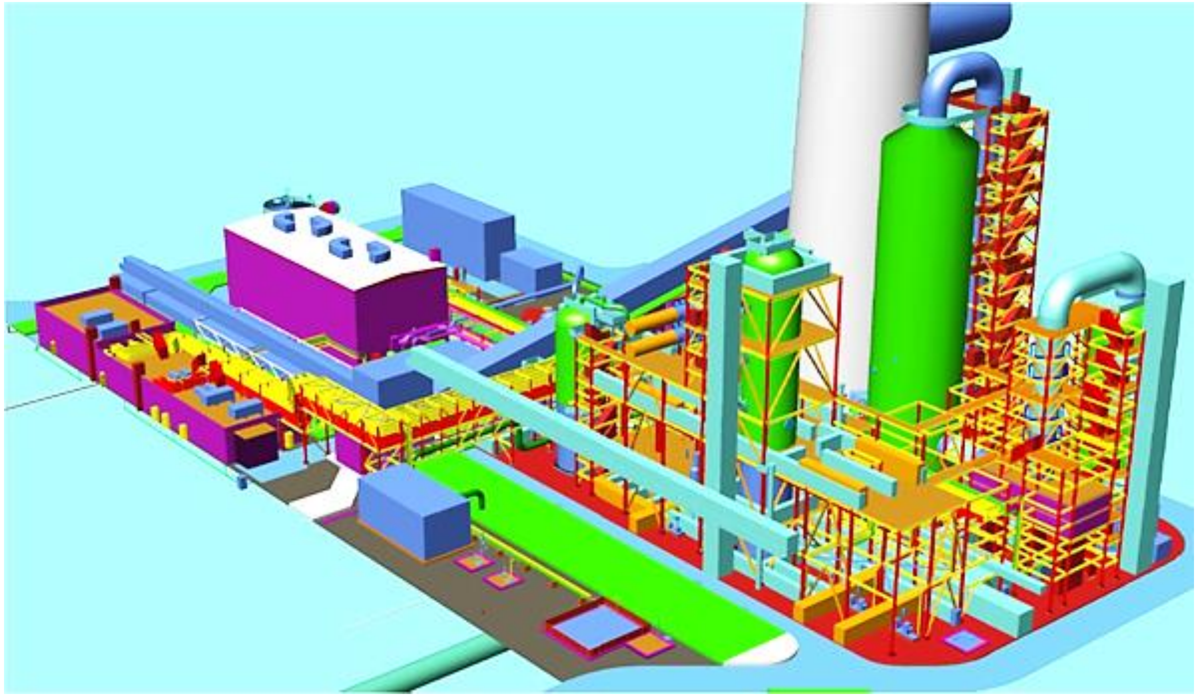
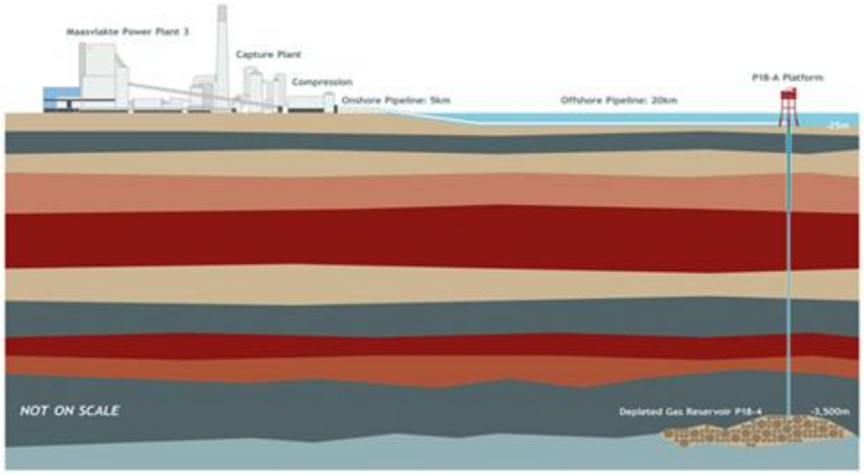


ROAD OBJECTIVE

- Demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain deployed on power generation

- ROAD was a joint project by E.ON Benelux and Electrabel Nederland (now Uniper Benelux and Engie Nederland, respectively)



- Wealth of data, a summary of which is included in 11 online reports: https://ccsnetwork.eu/projects/road-project-rotterdam

MAASVLAKTE POWER PLANT 3 (MPP3)

- MPP3 includes a pulverized-coal fired supercritical boiler (285 bar, 600 ^{o}C)
- Net electrical output is 1,069 MW

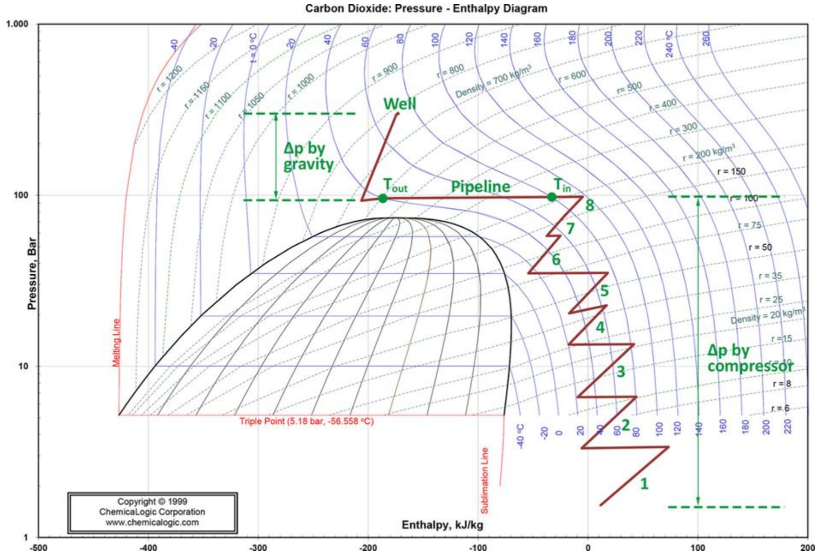
- Annual emission of CO_2: 5.7 Mt (base load operation)
- Carbon capture ready (TÜV Nord certified)

CAPTURE & COMPRESSION

- Designed capacity of 250 MWe equivalent
- 1.1 Mt CO_2 captured per year
- Fairy conventional layout of post-combustion capture amine process (Fluor)

- Design characteristics of a full-scale commercial plant:
  - Design life of 126,000 operating hours over 20 yrs
  - Ramp rates similar to power plant (up to 5%/minute)
  - Turndown to 40% capture rate

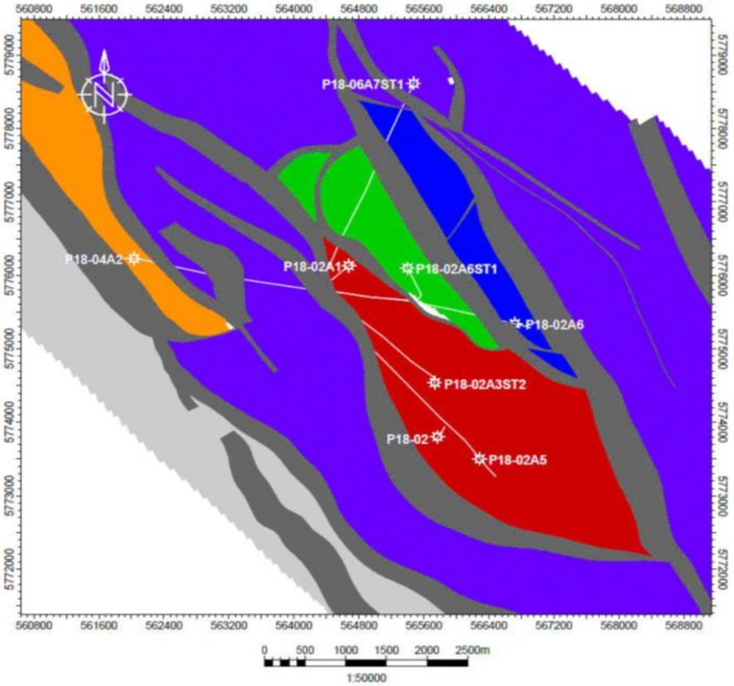
- P18-4 gas reservoir: 8 stage compressor to 129 bar
- Q16-Maas gas reservoir: 4 stage compressor to 19-22 bar



TRANSPORT & STORAGE

P18-4 gas reservoir

- Pipeline capacity of 5 Mtpa
- Max design pressure of 140 bar
- Reservoir storage capacity of 8 Mt
- 20 km off the coast
- Depth about 3.5 km below the seabed



Q16-Maas condensate gas reservoir

- Pipeline capacity of ≥ 6 Mtpa
- Max design pressure 40 bar
- Final compression to around 80 bar at injection site
- Reservoir storage capacity of 2 to 4 Mt
- Just offshore the Maasvlakte
- Deviated well to reservoir at 3 km depth

ROAD HISTORY

2009: Start feasibility and FEED studies

2012: Project developed to FID & permitting completed

Collapse of carbon price and no economic FID possible

In slow mode, reducing funding gap

2013: P18-4 irrevocable storage permit granted

2014: New funding structure & alternative store Q16-Maas

2016: Remobilisation of project

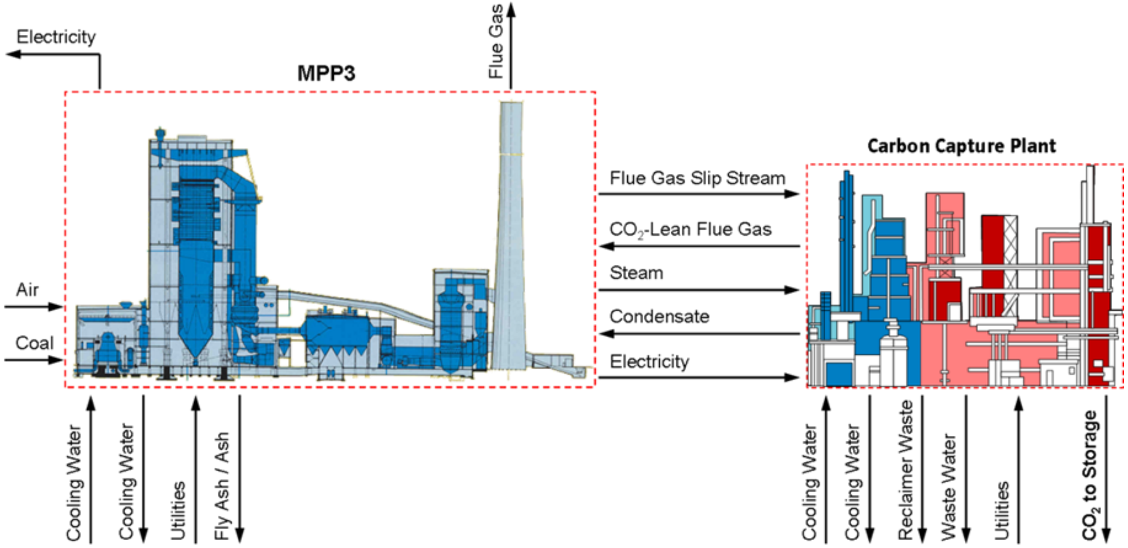
2017: Updated design of capture installation

Industry partners pulled out because of lack of political and financial support

HIGHLIGHTS: CAPTURE (I)

Power plant integration

- CO_2 from stripper cooled with power plant feedwater
- Steam ejector in power plant for efficient capture at part load
- Direct Contact Cooler condense water re-used for de-SOx



HIGHLIGHTS: CAPTURE (II)

Process performance & capture efficiency

- Capture efficiency 90% at full load
- Can be maintained at 90% or higher at part load

- Use of electricity and steam by capture plant single biggest cost

- Total (equivalent) electricity consumption of 58.4 MW (~ 23% of capacity)
  - Including all compression power
  - Including 3 MW of off-design operation
  - Excluding electricity consumption of WESP
  - Excluding additional consumption due to less efficient compression at Q16-Maas

- Details confidential because of Fluor trade secret
- Space for further performance improvement

HIGHLIGHTS: CAPTURE (III)

Wet electrostatic precipitator (WESP)

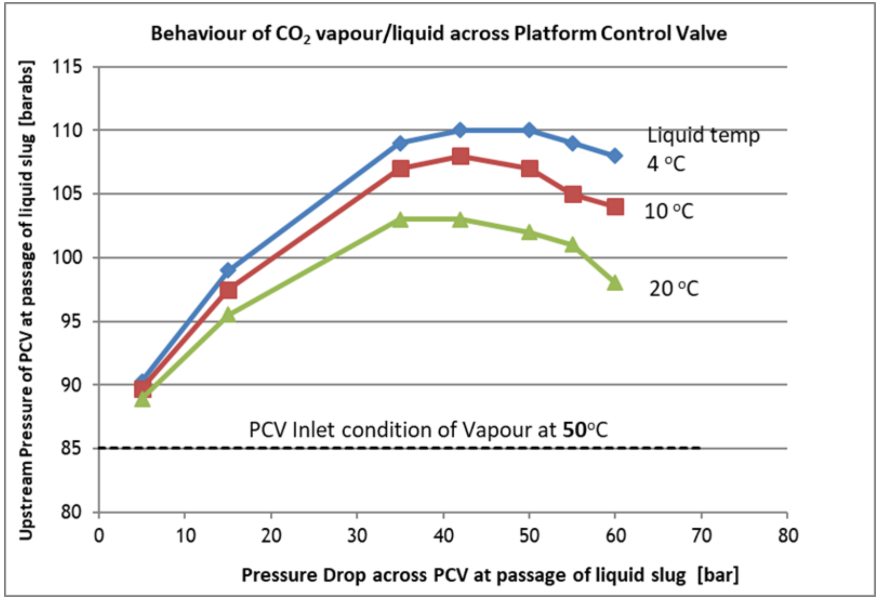
- Removing (SO_3) aerosols before absorber to prevent high solvent emissions
- Up to 99% may need to be removed ; the actual level is uncertain.
- A lower specification of 90% included in the design with space for an optional 2^{nd} WESP
- Location after the Direct Contact Cooler to minimize the risk of converting SO_2 to SO_3

Improved solvent management package

- Iron leaching into the solvent from the coal ash and Iron catalysed corrosion of the steel
- Testing of solutions at Wilhelmshaven pilot, e.g. Iron removal, improved reclaimer and filters
- Fluor developed a successful proprietary package after 2,00 hours test run at the Wilhelmshaven pilot

HIGHLIGHTS: TRANSPORT & STORAGE

- Two-phase flow and transient conditions in pipeline potentially causing:
  - Slugging in the pipeline
  - Thermal effects in well and reservoir
- Preliminary calculations of slugging risk
  - Likely no harm to equipment
  - Minimize by emptying the pipeline during shutdowns
  - Maintain low flow rate in initial phase
- Injection of cold CO_2 in P18-4 reservoir
  - Propagation of fractures may occur at temperature difference of more than 100 °C
  - Detailed analysis (TOUGH2/ECO2M) for P18-4 showed no fracturing as a result of injecting cold CO_2



CHALLENGING PERMITTING REQUIREMENTS

- Conditions for transfer of responsibility
  - All available evidence indicates complete and permanent containment
  - A minimum period elapses until above point has been met (default 20 yrs)
  - Financial obligations have been fulfilled
  - Site is sealed and installations removed

- 20 year period is very costly
- Unknown how 20 year period can be reduced
- Unknown if transfer could be postponed
- Unwanted uncertainty on the EUA price

- Much uncertainty on the handover criteria in particular for demoprojects

IN CONCLUSION (I)

- Capture, transport and storage technology is available and will work.
- FID-ready, permitted capture plant design for coal-fired power plant at 250 MWe scale

- Successful design of interfaces along the whole power chain
- Handling of injection of CO_2 into low pressure depleted gas reservoirs successfully engineered

- Regulatory barriers to permitting successfully overcome
- First CO_2 storage permit under the CCS Directive granted in TAQA's P18-4 gas field

IN CONCLUSION (II)

- Future CCS project developers are recommended to stay close to the research community to ensure state-of-the art engineering

- Design of transport requires careful tuning to the storage location and characteristics

- Experience points the way forward for the future use of depleted gas reservoirs for storage

- Requirements for monitoring, financial security and transfer of responsibility may change over time and thus represent a big uncertainty.
- Strong national support is necessary to overcome these uncertainties and requires early start of collaboration with the authorities.

CO-FINANCED BY:

- The European Commission
- The Netherlands Government
- Global CCS Institute
- Port of Rotterdam

THANK YOU FOR YOUR ATTENTION

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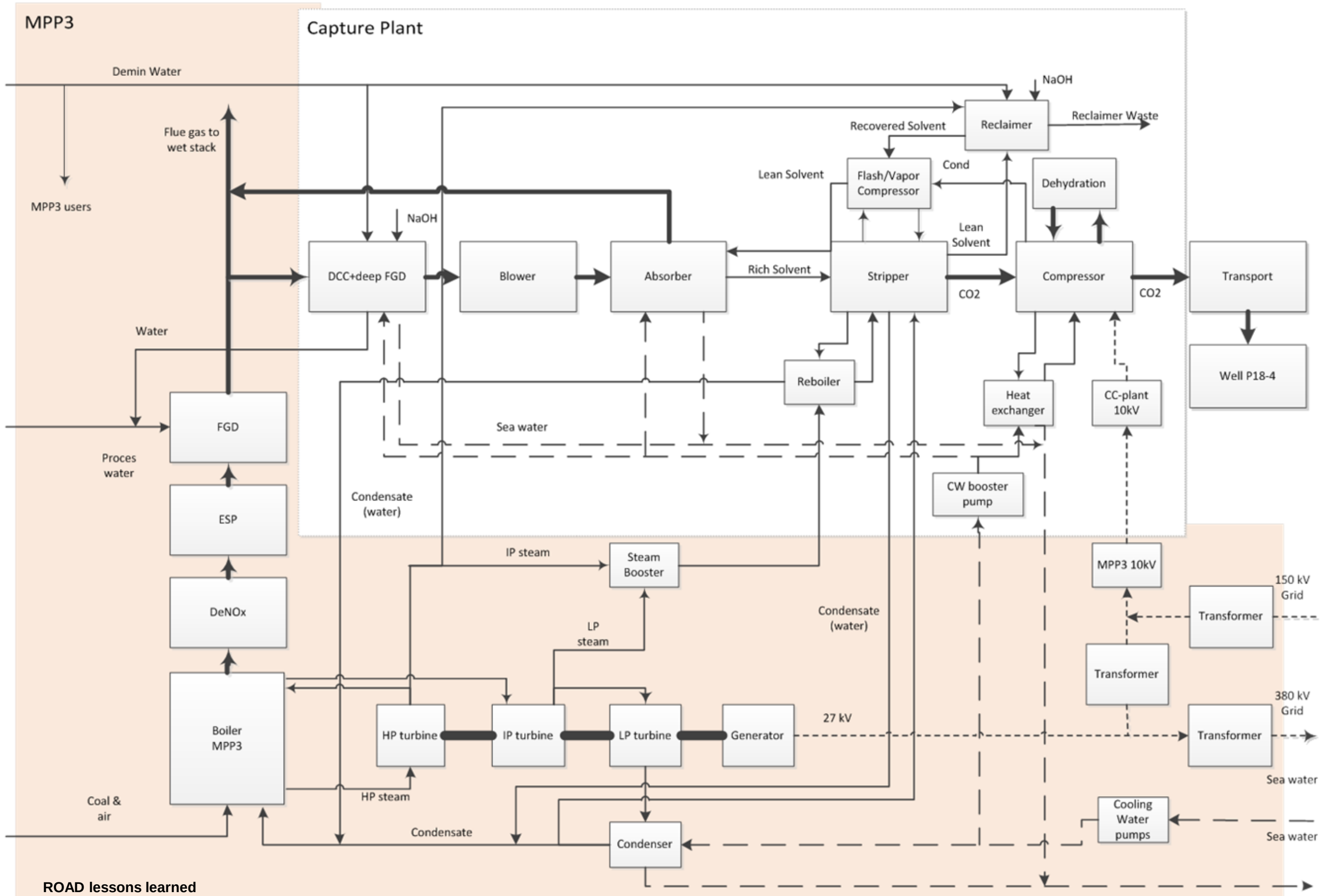
THE ROAD CCS CHAIN INTEGRATED IN THE MPP3



ROAD lessons learned