TNO innovation for life

DEVELOPING CCS IN THE NETHERLANDS: PORTHOS PROJECT

FILIP NEELE, TNO

JANUARY 24 2023, TOKYO

CO_2 STORAGE / THE NETHERLANDS / PORTHOS PROJECT

USING DEPLETED FIELDS FOR CO_2 STORAGE

TNO – WHO WE ARE

CCS IN THE NETHERLANDS

PORTHOS CCS PROJECT

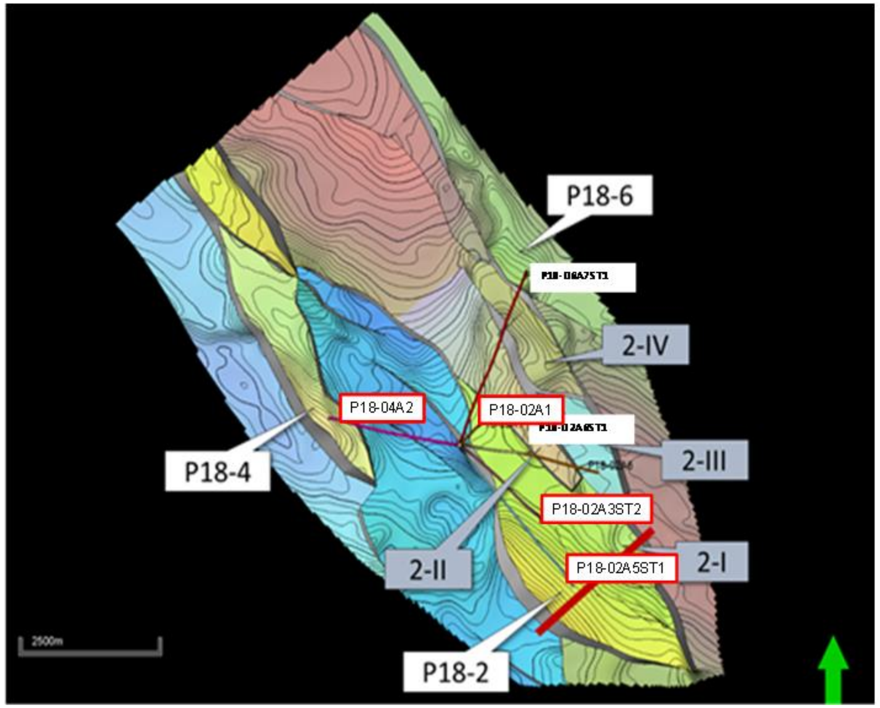
INTERMEZZO: CO_2 FLOW INTO DEPL. FIELDS

PORTHOS: FAULT STABILITY

PORTHOS: WELL INTEGRITY & MONITORING

CONCLUSIONS

ONGOING R&D WORK



TNO innovation for life

» TNO IN SUMMARY

TNO is the leading Dutch independent applied research and innovation institute

Independent organization with 3,600+ professionals

Turnover of EUR 550+ M in 2020 – 40% governmental, 30% business – ~20% international

With depth and breadth of knowledge, multidisciplinary

Focused on smart solutions to complex issues

With the aim of sustainably strengthening the competitiveness of industry and the well-being of society

Together with partners: companies, organizations at home and abroad

TNO innovation for life

TNO ENERGY TRANSITION & MATERIALS – IN SHORT

- With 700+ scientific experts and advisors, TNO’s ETM unit works towards developing a climate resilient and sustainable society, to support a thriving economy

- We take an agenda-setting, initiating and supporting role in the energy transition and bring entrepreneurs, scientists and policy makers together to contribute to a sustainable life and a brighter future

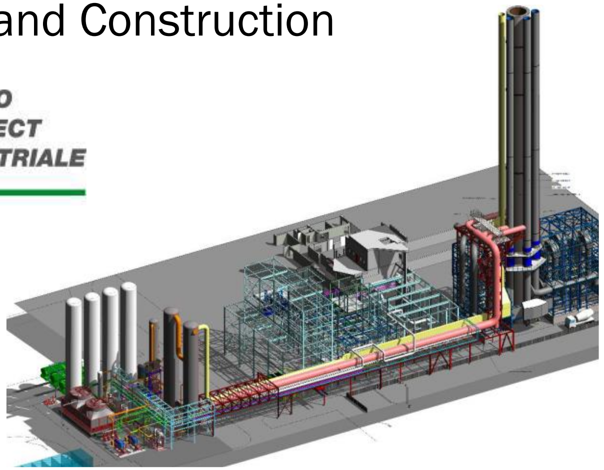
- As the national research institute, we strive to accelerate the energy transition so that in 2050 the Netherlands will have an energy regime free of CO_2 emissions

- We are the national knowledge centre on the energy transition, with an international outlook: we have four integrated innovation roadmaps, focused on biggest challenges in the energy transition:

AVR. DUIVEN
OPERATIONAL CAPTURE @ WASTE INCINERATOR

Engineering, Procurement and Construction

TPI TECNO PROJECT INDUSTRIALE
SIAD Group



Solvent:
30wt% MEA
(flexible)

Distribution of liquid CO_2 to greenhouses

Air Liquide
creative oxygen

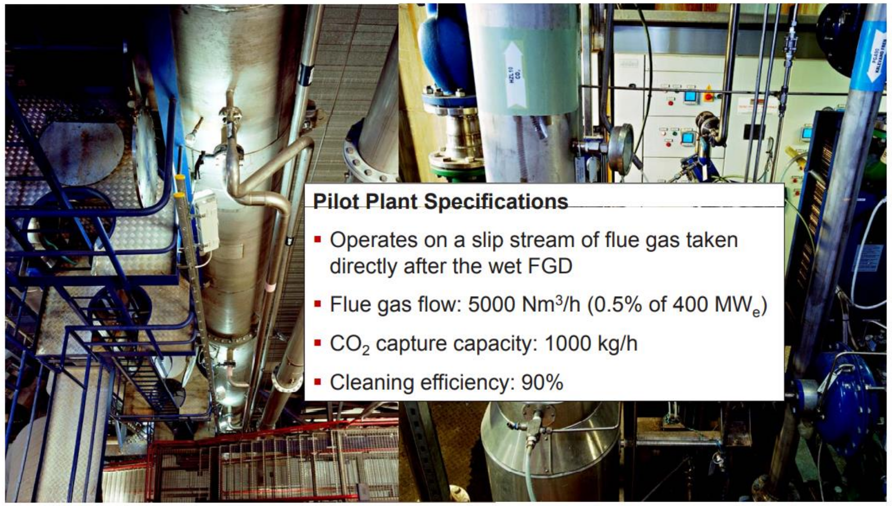
TNO's role: providing valuable information to help AVR in preparation to find a suitable partner to build the large-scale carbon capture plant and staying close at hand throughout commissioning and operational stages, supporting with in depth process analysis from the start of the plant's operation.

TNO CO_2 CATCHER
250 KG OF CO_2 PER HOUR

- Location Rotterdam at E.ON Coal fired powerplant (2007-2012)

EXAMPLES OF TNO TRACK RECORD RELATED TO CAPTURE PLANT DESIGN AND OPTIMIZATION

TNO pilot plant (2007-2012)



Pilot Plant Specifications

- Operates on a slip stream of flue gas taken directly after the wet FGD
- Flue gas flow: 5000 Nm³/h (0.5% of 400 MW_e)
- CO_2 capture capacity: 1000 kg/h
- Cleaning efficiency: 90%

DONG pilot plant (2008-2011)

AVR 100 ktpa plant (2016)
(waste incineration)

TWENCE $KHCO_3$ plant

TNO mobile capture plant

MAIN RESEARCH FACILITIES ON POST COMBUSTION CO_2 CAPTURE

On-site CO_2 Capture Services

- On-site diagnosis

  Evaluate the quality of the flue gas, and estimate the impact of impurities and particles on a future CO_2 capture plant

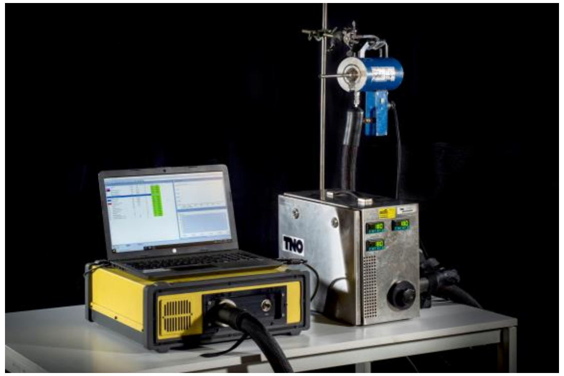
  - FTIR: gas composition, including acidic impurities that can lead to the formation of heat stable salts
  - ELPI+: characterization of particles on a size range that could lead to aerosol-based emissions
  - Evaluation of the flue gas under dynamic conditions (e.g.: change of fuels, maintenance in the line)

- Mobile CO_2 capture pilot plant

  Evaluate the flue gas-solvent interactions, and how that reflects in solvent degradation and emissions. Test solvent management strategies and emission mitigation technologies

  - The plant is flexible and can run on different solvents
  - Track record includes: MEA, aMDEA, aminoacid salts, etc.

Flexible, mobile equipment


FTIR


ELPI+

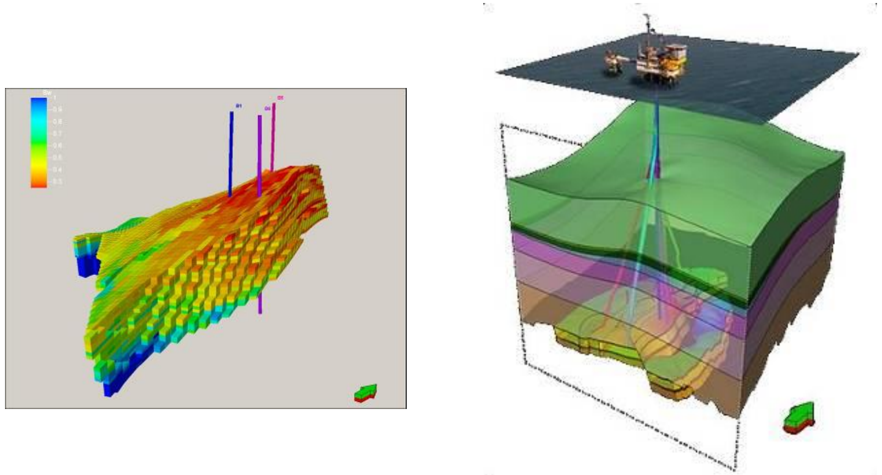

Miniplant

TNO HAS A STRONG TRACK RECORD ON CO_2 STORAGE AND TRANSPORTATION

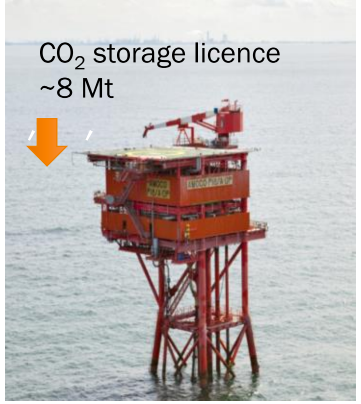
TNO has a leading role in the EU and nationally on R&D in CO_2 transport and storage. TNO's expertise covers all elements that are needed to bring a potential storage site to permit level, such as storage site characterization, monitoring, well integrity, storage optimization (& EOR), transport networks, flow assurance, fault stability, natural sealing, site closure, conformance, policy & regulations, CO_2 quality specification, risk assessment, site screening, ship transport, buffering, decommissioning, societal embeddedness, stakeholder involvement.

TNO has been involved in CO_2 injection (the K12-B field), has developed the basis for storage permits (depleted fields, saline formations), has developed the design of transport pipelines and injection wells (for the ROAD and Porthos CCS projects in The Netherlands).

TNO has led the CATO M€ 60 R&D CCS R&D program in The Netherlands (2004 – 2014).



K12-B: pilot CO_2 storage (2004 – 2014)



Depleted field storage: Porthos – P18 cluster (2009 – present)

TNO WELL TECHNOLOGIES LAB FACILITIES

Rijswijk Centre for Sustainable Geo-energy (RCSG)

Ministry of Economic Affairs and Climate Policy

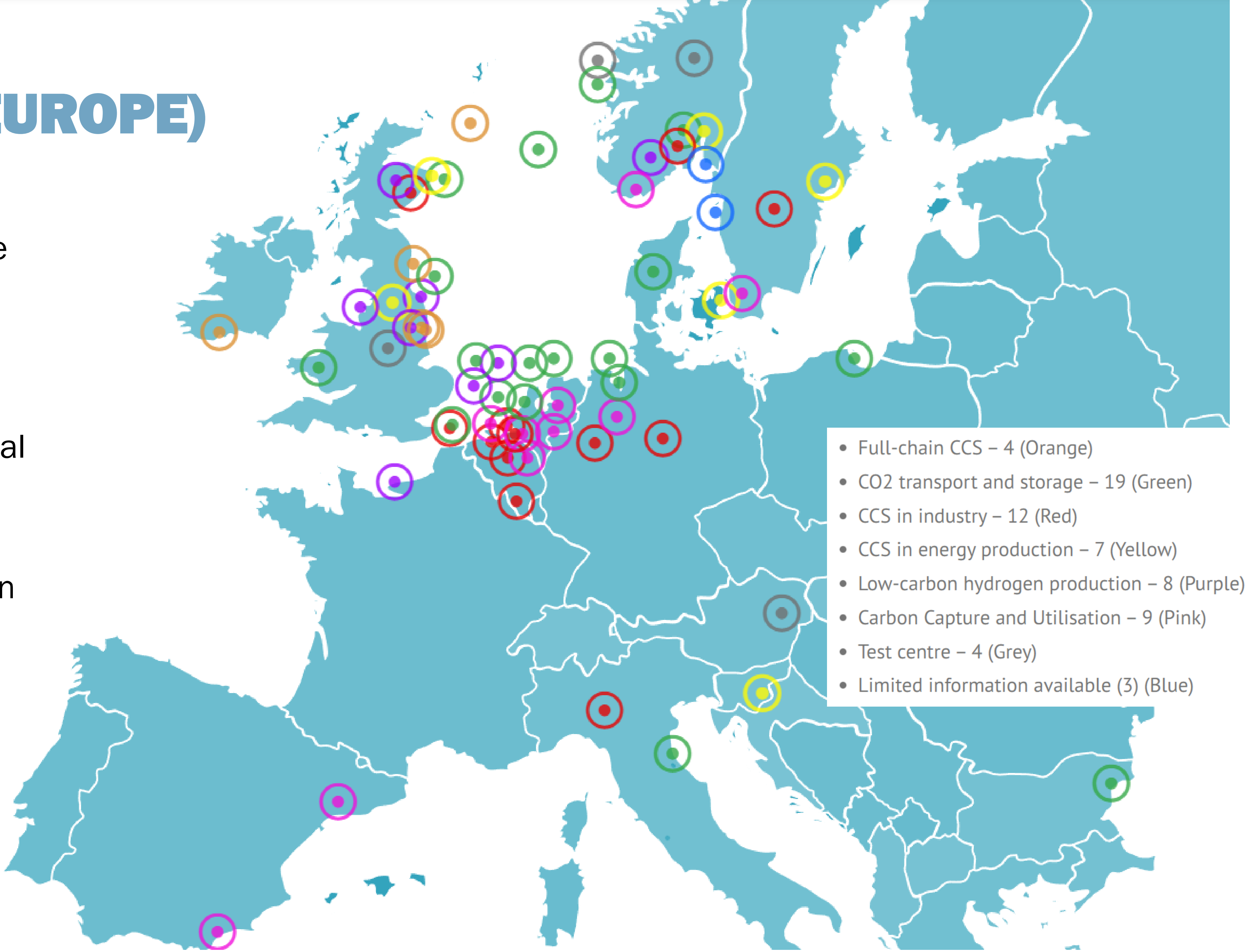
ebn

provincie Zuid Holland

Rijswijk

CCS PROJECTS (EUROPE)

- Many CCS projects around the North Sea
  - Linking onshore emitters to offshore storage capacity
- Many projects close to financial investment decision; many projects in feasibility phase
- Several projects to be online in period 2025 - 2030
- Transport to these projects
  - Pipeline, ship



- Full-chain CCS – 4 (Orange)
- CO2 transport and storage – 19 (Green)
- CCS in industry – 12 (Red)
- CCS in energy production – 7 (Yellow)
- Low-carbon hydrogen production – 8 (Purple)
- Carbon Capture and Utilisation – 9 (Pink)
- Test centre – 4 (Grey)
- Limited information available (3) (Blue)

https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/, 2022

CCS PROJECTS NL
OFFSHORE GAS FIELDS

- Abundant storage capacity, developing it is a challenge!
  - Potential timeline of field development
  - Ranking of options – unit storage cost, location, capacity, etc.
  - Low or very pressure after production
  - **Porthos**

DCS: Dutch continental shelf
DGF: depleted gas field
DSF: deep saline formation
P18: gas field cluster developed by Porthos

~1000 Mt in many gas fields

K14-K15 cluster, F4 fields
Shell, TotalEnergies
Start 2026/7

Q1 cluster
DGF, DSF
Wintershall, Petrogas
Start 2027+

New pipeline (**Aramis**)
~200 km,
Capacity 22 Mtpa
Start 2027

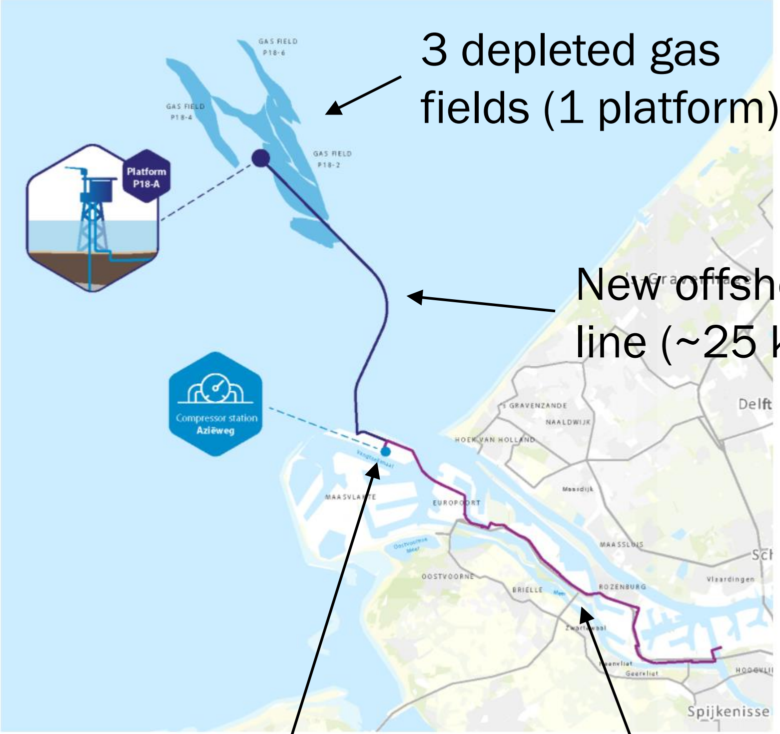
Porthos
(~25 km dist.)
Start 2025/6

P18 cluster
35 Mt

PORTHOS CCS PROJECT
KEY FACTS

- Porthos: first of a kind CCS project for NL
  - Multiple depleted gas fields
  - Multiple suppliers
  - Large-scale operations
- Developing CO_2 transport and storage service to emitters in Rotterdam area
  - First phase: 2.5 Mtpa, 4 emitters (CO_2 from H_2 production)
  - Storage: depleted gas fields (<20 bar!), ~37 Mt capacity, storage permit applications approved 2022 / 2023
  - Timeline: FID Q1/2-2023, start injection 2024 – 2025
  - Injection period: 15 years
- Project structure
  - Joint development: Porthos + 4 emitters
  - Support from national subsidy and EU funds
  - Emitters: ETS + floor price guarantee (national subsidy, 15 yrs)

Porthos website: https://www.porthosco2.nl/en/



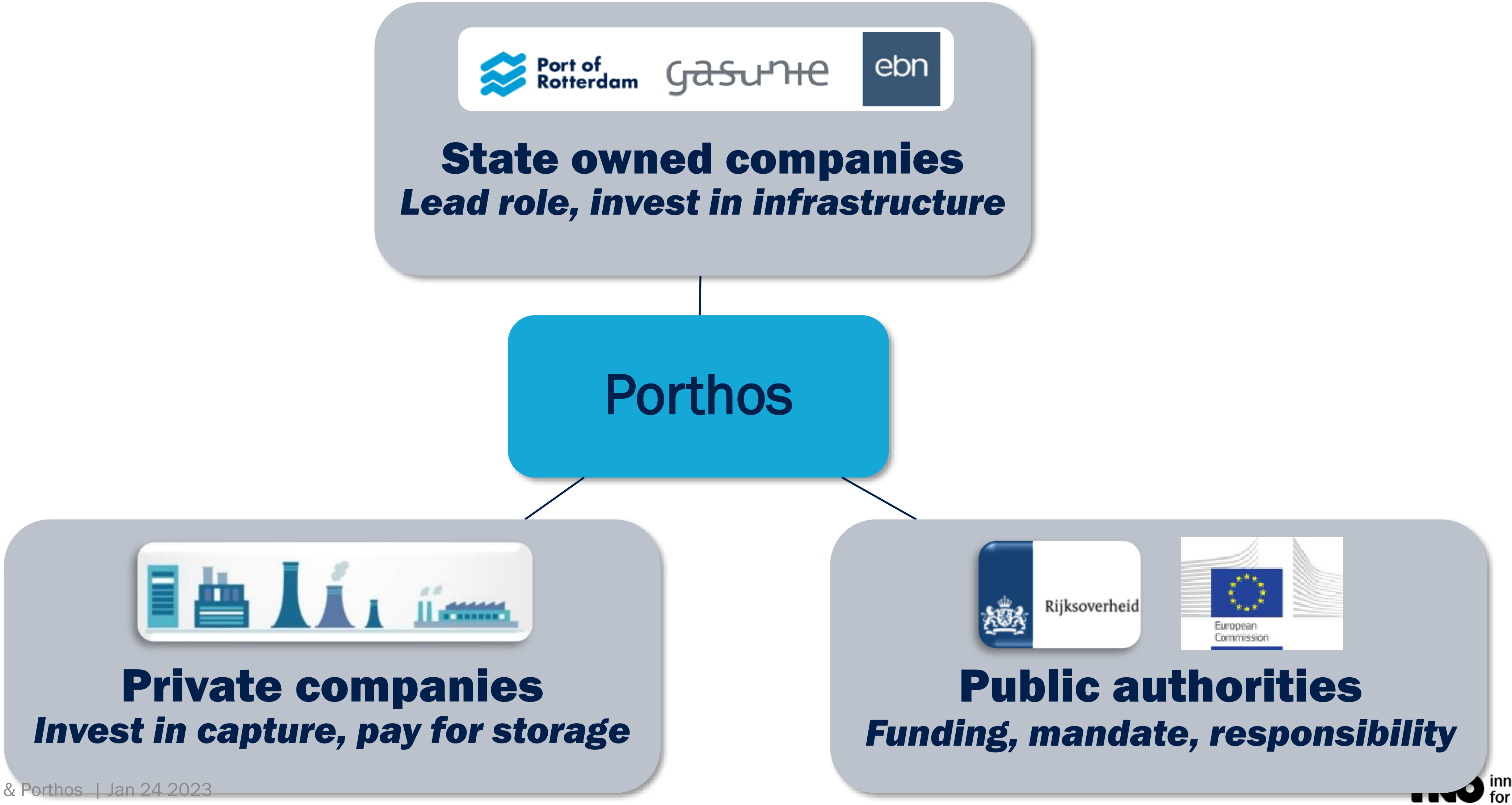
3 depleted gas fields (1 platform)

New offshore line (~25 km)

Shipping terminal (CO2next) (not part of Porthos)

Collection network in Rotterdam Port; 4 suppliers

PUBLIC-PRIVATE PARTNERSHIP FOR SUCCESSFUL CCUS



State owned companies
Lead role, invest in infrastructure

Porthos

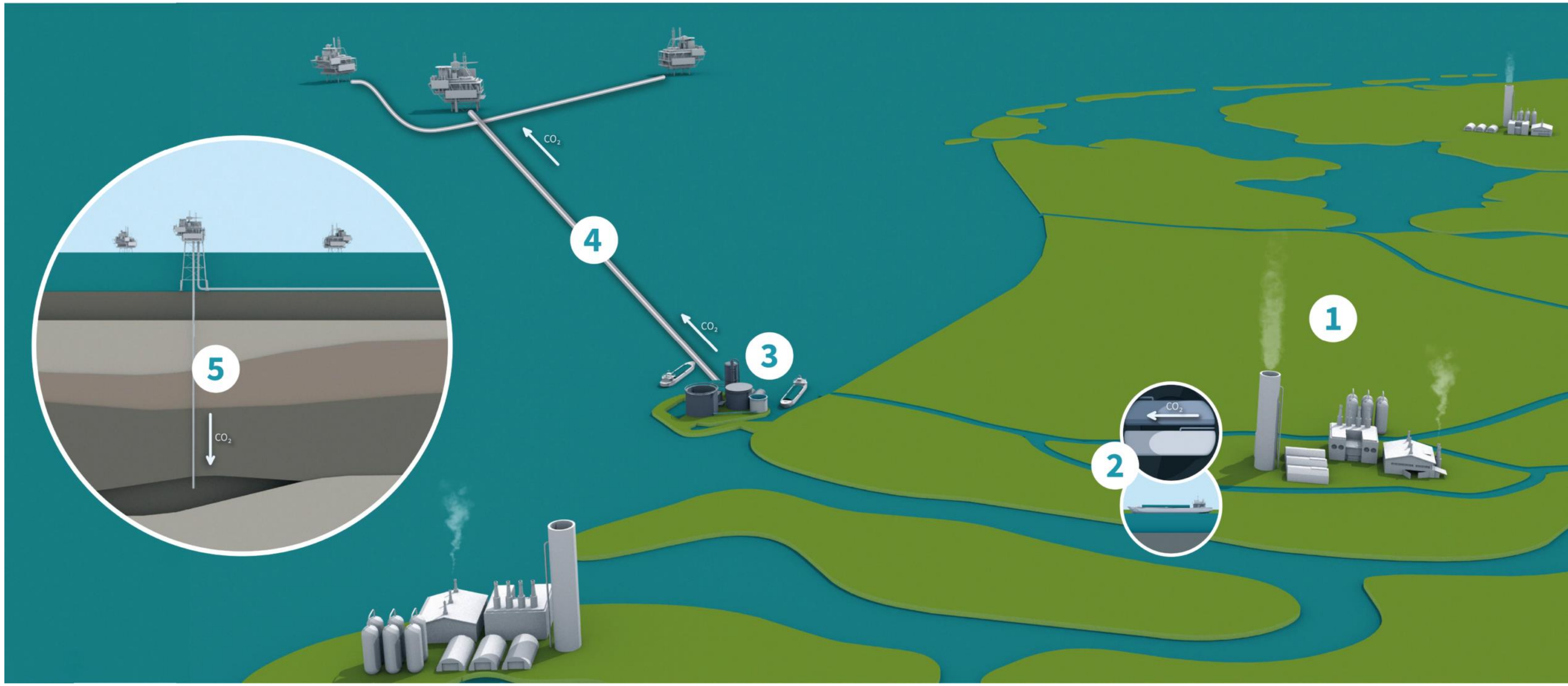
Private companies
Invest in capture, pay for storage

Public authorities
Funding, mandate, responsibility

ARAMIS CCS PROJECT
THE 2ND CCS PROJECT UNDER DEVELOPMENT

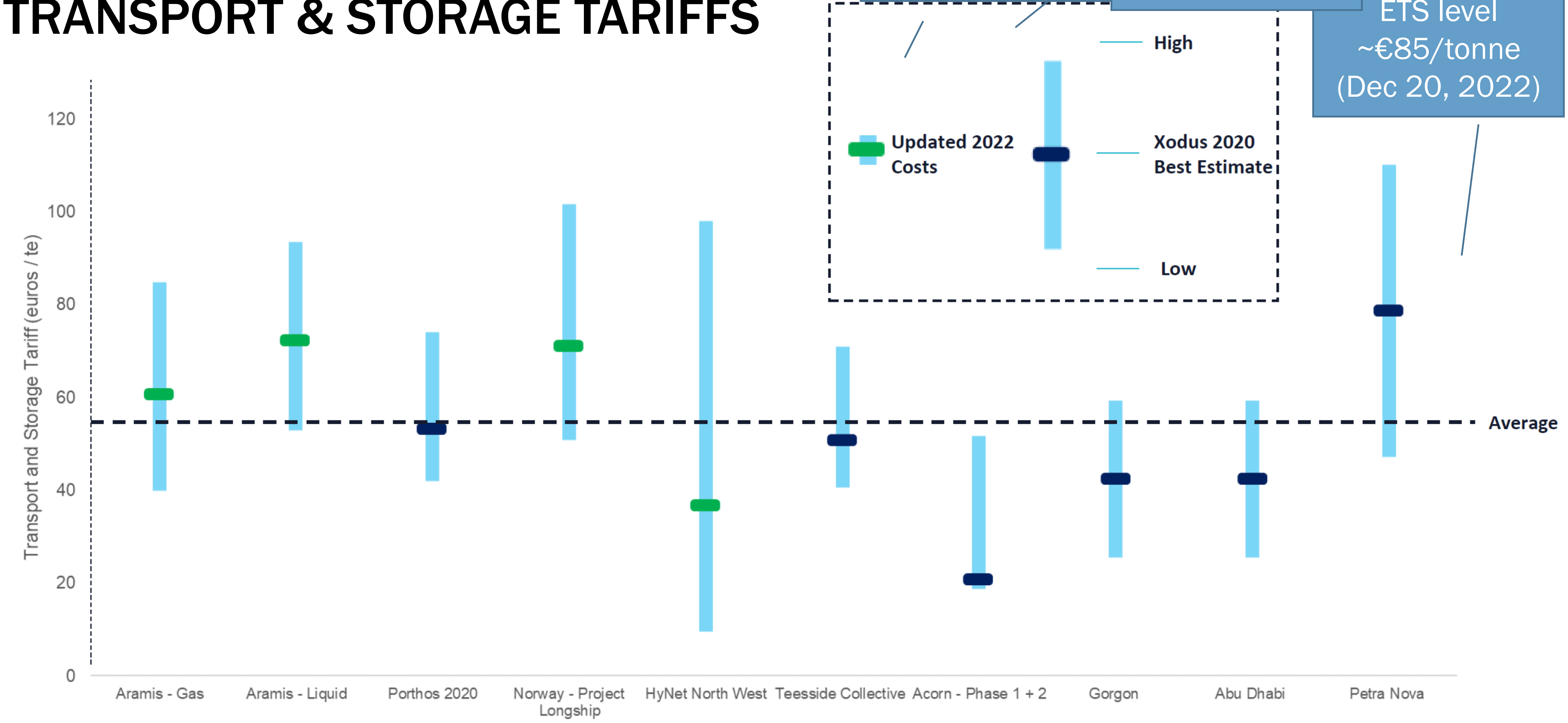
- 1. Emitters in Rotterdam Port and in hinterland
- 2. Collection network
- 3. Compression to 130 bar or higher
- 3. Shipping terminal CO2Next
- 4. Offshore backbone pipeline, capacity 22 Mtpa
- 5. Storage in depleted offshore reservoirs

- Timeline: operational by 2026-2027



https://www.aramis-ccs.com/

CCS IN NL: COST ESTIMATES
TRANSPORT & STORAGE TARIFFS



Capture costs to be added

Transport *to* the projects not included!

ETS level ~€85/tonne (Dec 20, 2022)

*Aramis assumes 40% CEF Funding and excludes Porthos onshore pipeline tariff

*Xodus report on cost statements by Porthos and Aramis, 2022

[PowerPoint Presentation (staten-generaal.nl)]()

INTERMEZZO
FLOW ASSURANCE ISSUES

- The flow assurance challenges in CO_2 storage in depleted gas field consist of:
  - **Low temperature in the well** (wellhead, subsurface safety valve (SSSV), at bottom hole)

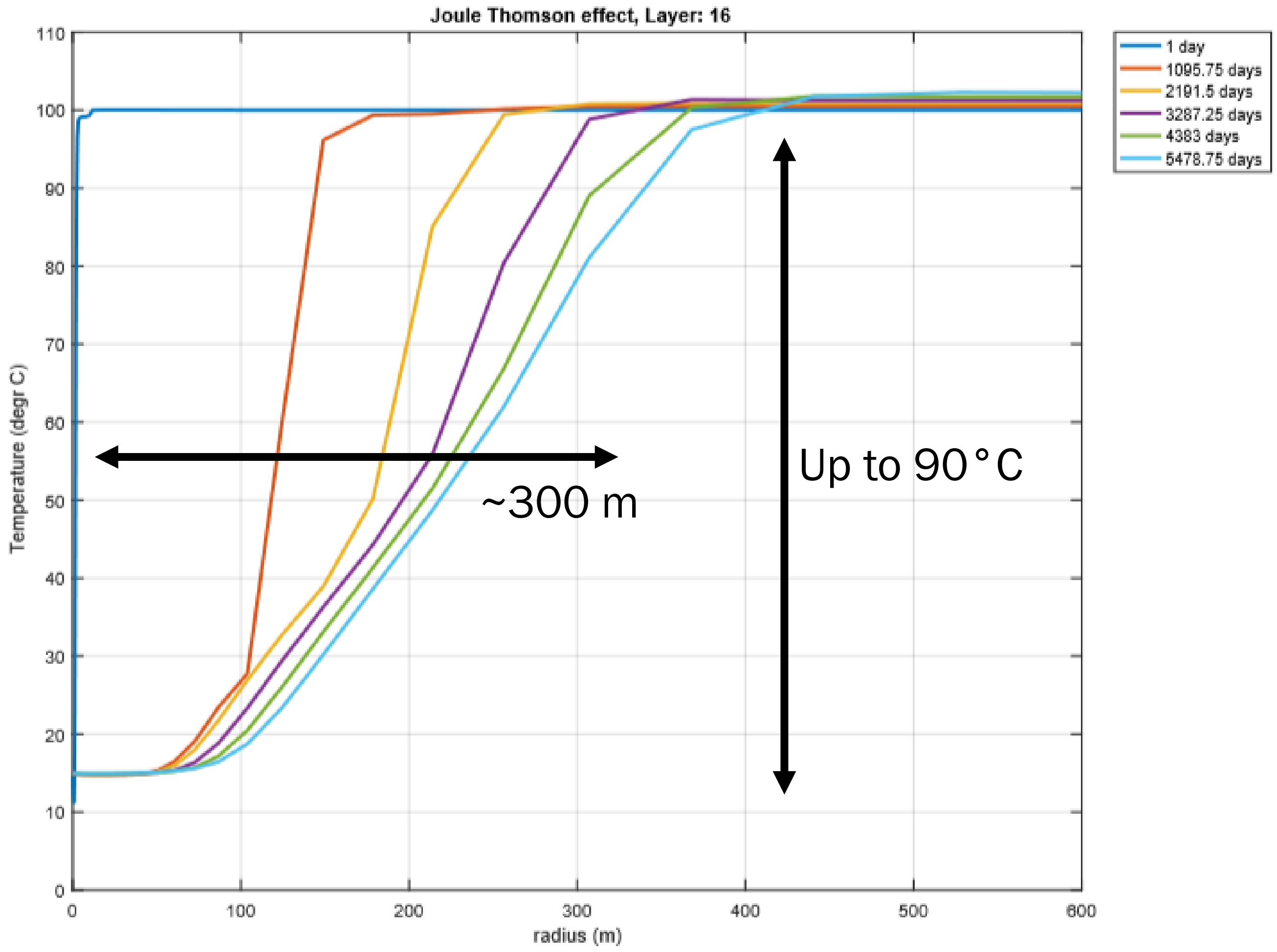
    Potential for freezing annulus fluids, malfunctioning of the SSSV, hydrate formation in or near the well

  - **Low temperature in reservoir**

    A cooling front extents into the reservoir as cold CO_2 is injected for a longer time

    This can potentially re-activate faults

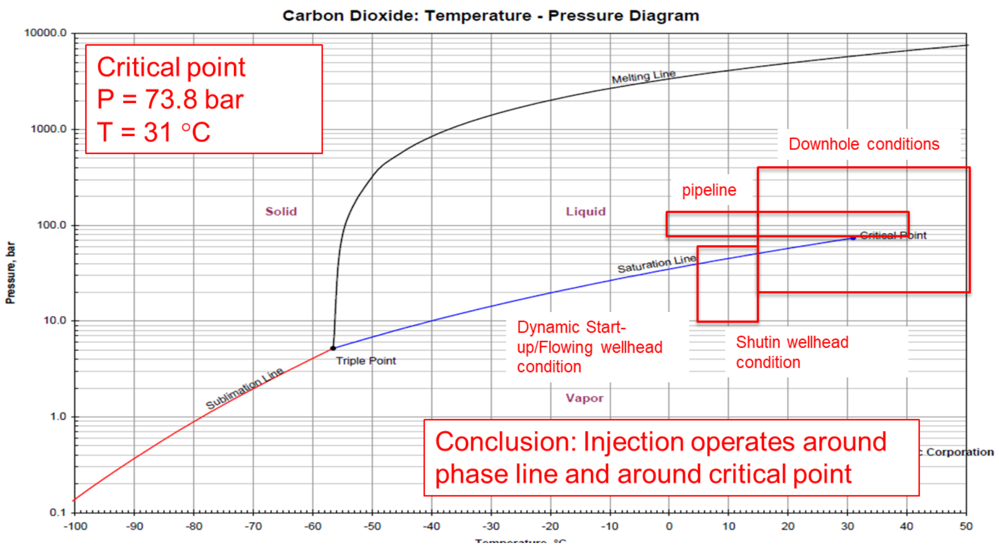
  - **High pressure drop between well and reservoir**
  - ‘Normal’ issues such as erosion, vibrations



Temperature front in the P18-2 field, after injecting CO_2 at 15 °C for up to 15 years. In this reservoir, the low-temperature zone does not extend more than about 200-300 m from the well

INTRODUCTION
LOW TEMPERATURE

- Low temperature in the well occurs when the fluid is at the phase-line
- The pressure drop in the well is a combination of gravity head and frictional losses
  - Due to gravity, the pressure will decrease from downhole to wellhead
  - Due to friction, the pressure will increase from downhole to wellhead
- At lower flow rates, the gravity component dominates. This means that the required wellhead injection pressure is lower than the reservoir (bottomhole) pressure.
- However, the default pipeline operating conditions are in liquid phase (typical pipeline operating pressure 85 – 120 bar). This means that at normal transport temperatures (5-15 °C) the conditions downstream from control valves will be in the two-phase domain and therefore at low temperature



Critical point
P = 73.8 bar
T = 31 °C

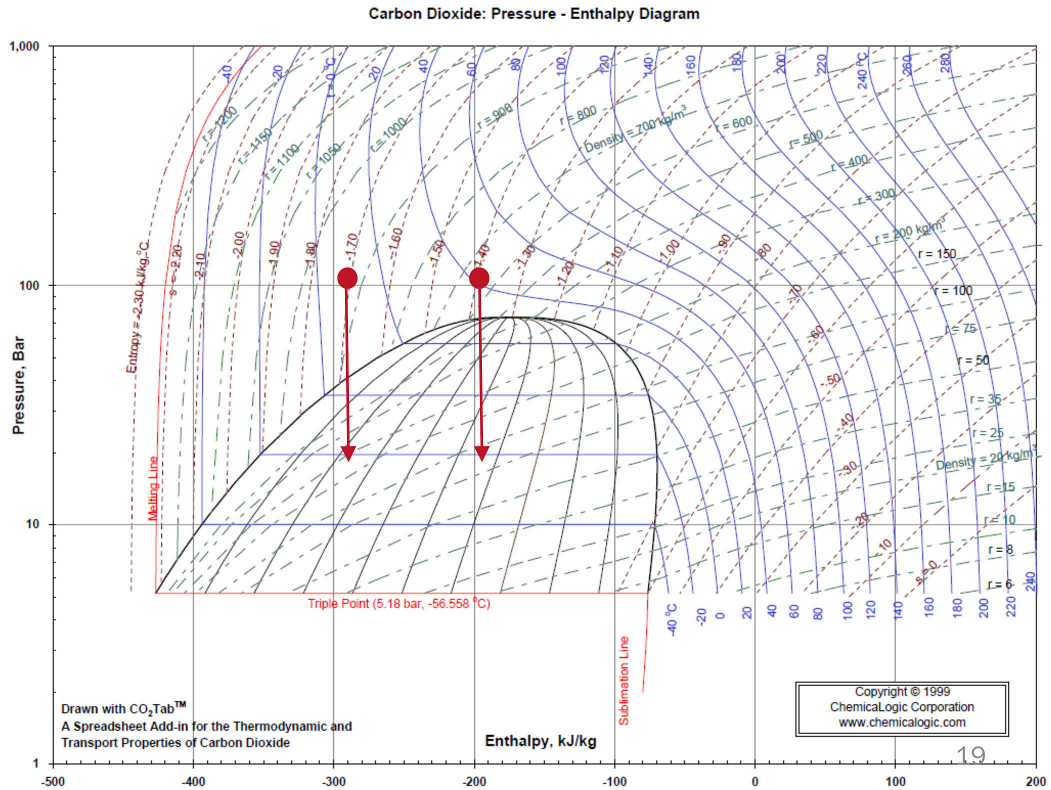
Downhole conditions

pipeline

Dynamic Start-up/Flowing wellhead condition

Shutin wellhead condition

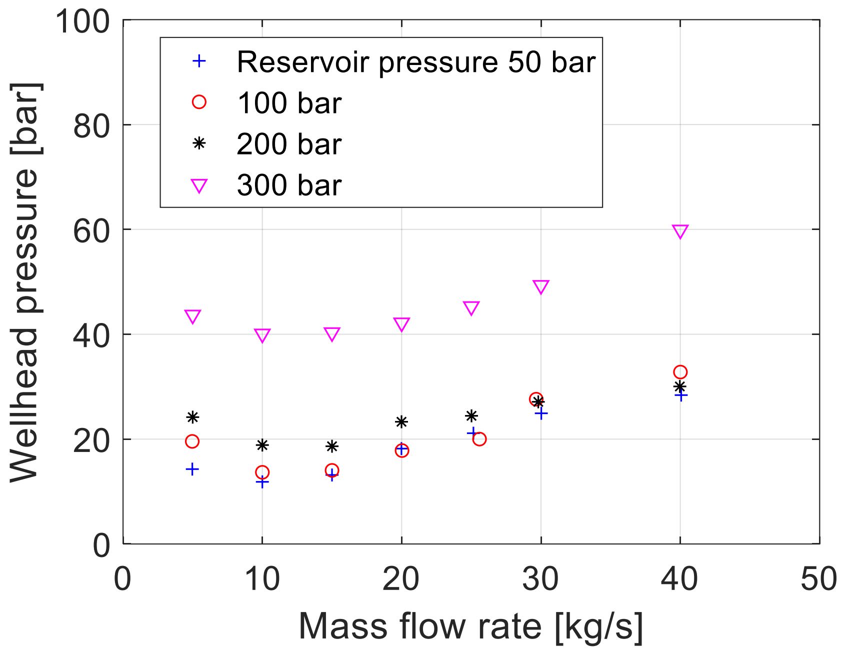
Conclusion: Injection operates around phase line and around critical point

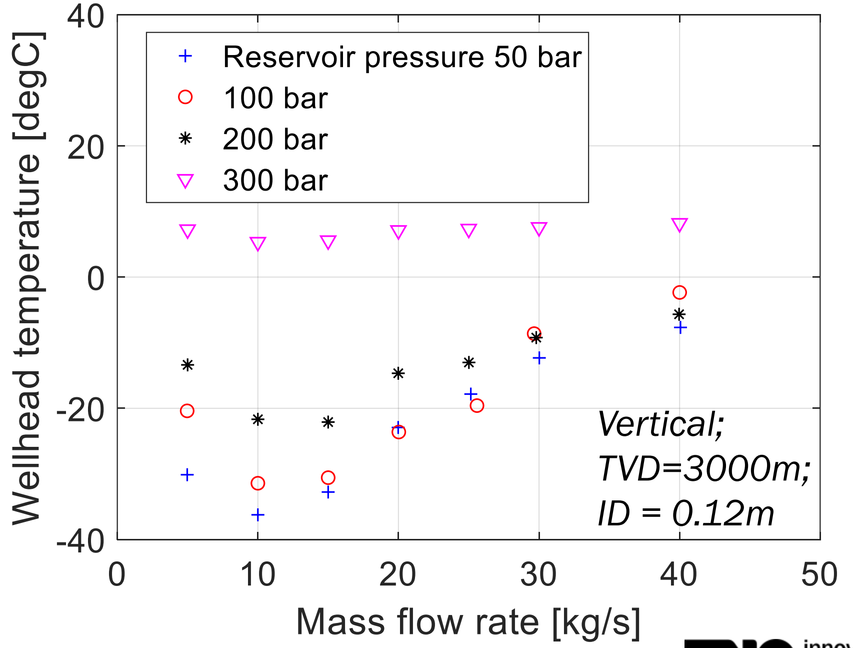


INTRODUCTION
WELL BEHAVIOUR

In principle this two-phase region in wells (and the associated low temperature) can be avoided:

- Increase the injection pressure
  - This reduces the pressure drop at control chokes.
    To avoid very high flow rates (risk of vibrations and erosion), the frictional pressure drop must be increased. This can be done by decreasing the tubing ID.
    This limits the operational range.
- Increase the transport temperature
  - This increases the minimum temperature in the well
- Lower the transport pressure
  - Rather than in liquid phase, transport in gas phase. This limits the pressure drop at control valves.
    The cost is limited overall injection rate.





INTRODUCTION
WELL BEHAVIOUR

- Therefore there is a number of potential operational scenarios depending on
  - Reservoir pressure
  - Reservoir permeability

- Wells with a low reservoir pressure
  - Lower than 50 bar have the potential of hydrate formation
  - Lower than 35 bar have the potential of sub-zero fluid temperatures (and therefore freezing)
  - Lower reservoir pressures lead faster to low wellhead pressures

- Wells with a high permeability (high injectivity)
  - The bottomhole pressure is almost equal to the reservoir pressure. Therefore, the pressure in the well remains low until higher flow rates and/or higher reservoir pressures. The well can handle high rates but temperature in the well can become very low. Typically, these wells have a minimum and maximum injection rate which results in challenges to operation

- Well with a low permeability (low injectivity)
  - The bottomhole pressure is high at low injection rates. Therefore, the pressure in the well is high and there are less temperature issues. But the injection rates are small and depend on the reservoir pressure. Operationally easy as in general the wells are open or closed. The injection rate can (typically) only be varied via the pipeline pressure.

PORTHOS SYSTEM
SYSTEM CONCEPT USED

- The Porthos system consists of
  - Low-pressure collection network in Rotterdam Port area
  - Compressor station at shoreline
  - Insulated offshore pipeline (~25 km)
  - 4 injection wells into two high-permeability reservoirs P18-2 and P1-4
  - Reservoir pressure

    At start injection: ~17 bar

    At end injection: ~ 340 bar

- The well injectivity is very high at the Porthos system. Therefore:
  - Use of insulated pipeline (U ~1-2 W/m^2K) to get the temperature at the platform to ~30-40°C.
    This is possible due to the short distance to the field
  - Injection in gas phase until the reservoir pressure is ~40-50 bar
  - Change to liquid/supercritical transport and injection at higher reservoir pressures

Reservoir:

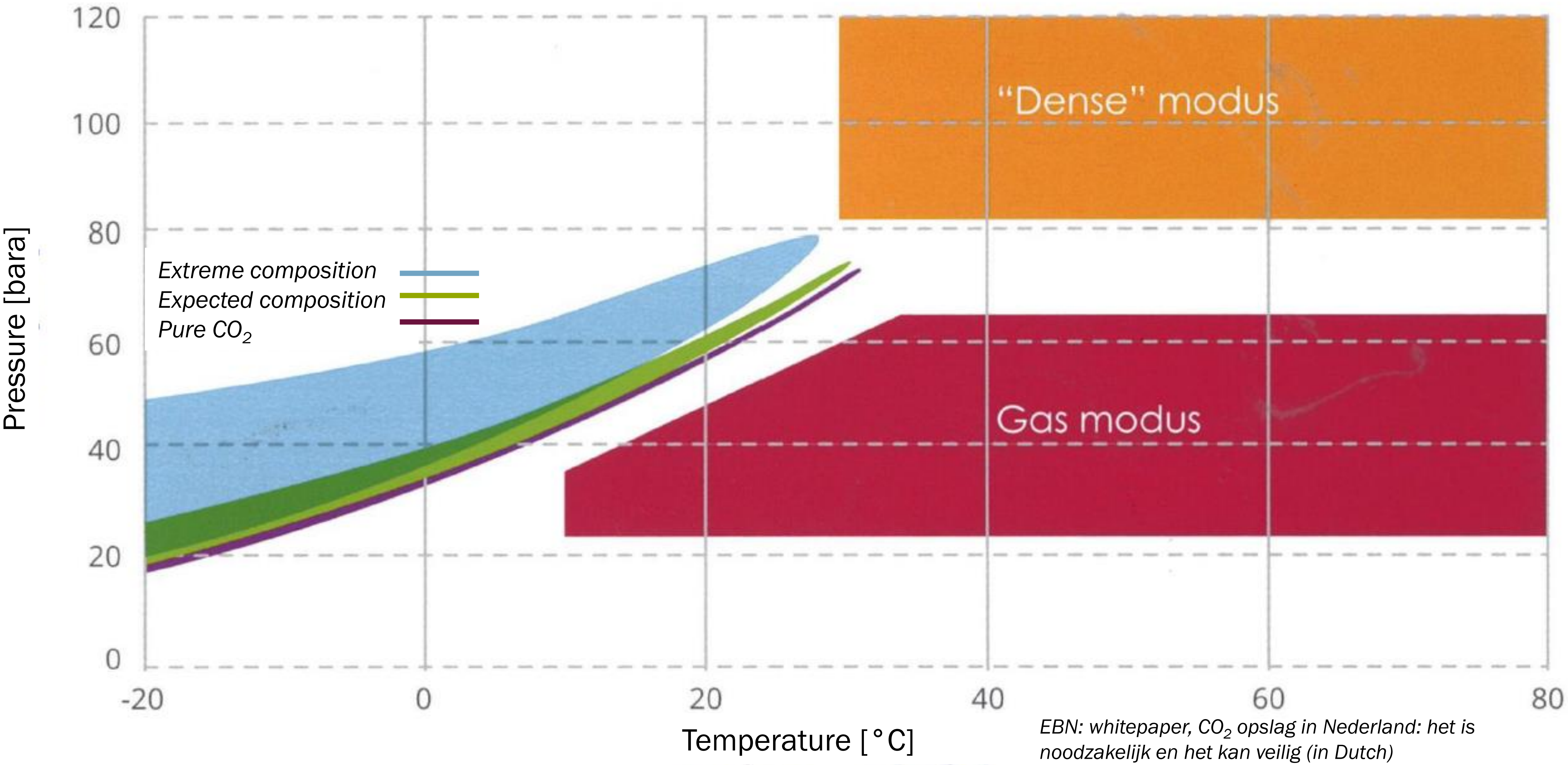
P18-2 P18-4

	P18-2A1	**P18-2A3**	**P18-2A5**	**P18-4A2**
kh [mDm]	3150	17426	22875	9175

Table of permeability times thickness for the two largest depleted fields in the P18 cluster

EBN: whitepaper, CO_2 opslag in Nederland: het is noodzakelijk en het kan veilig (in Dutch)
“CO_2 storage in The Netherlands: an essential and safe technology”
(download link)

Phase diagram and operational regions of the Porthos offshore pipeline



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DEVELOPING SAFE INJECTION INTO DEPLETED FIELDS
CHALLENGES

- The main (quasi) steady-state challenges are:
  - **Engineer** operational envelope (design insulation value pipeline and well IDs, under boundary condition of overall target rate)
  - **Define** injection strategy
    - Balance injection rates between the wells to avoid too large differences in reservoir pressure (which would lead to loss of operational flexibility)
    - Balance injection rates to limit the low temperature area around the wells to avoid fault re-activation (if relevant)

- The main challenges for the dynamic intervals during injection are:
  - With warm CO_2 required in steady state (*), the start-up after a long shutin is challenging. The pipeline can be in two-phase conditions, at seawater temperature. It takes time before warm CO_2 arrives at the platform. Therefore, the challenge is how to balance rates, ramp rates and injection rates.
  - Shut-in. As at no-flow the frictional part of the pressure drop falls away, a shutin can lead to low wellhead temperature (due to the gas expansion).
  - SSSV location and testing. Most current safety valves have a high temperature rating; avoiding low temperatures at all conditions is a challenge. Any potential leaks can also lead to sub-zero temperatures at the valve location during leak tests.

- Unknowns/uncertainties
  - Flashing in valves/chokes. Potential (droplet) erosion in chokes.
  - Vapour collapse at well start-up; vapour collapse in sidebranches.

(*) The P18 system uses warm CO_2 as key part of engineered injection solution. This is feasible because platform is at ~20 km from compressor

DEPLETED FIELDS: (SOME) OPERATIONAL LIMITS

EXAMPLE WELLS, HYDRATE LIMITS

- **Bring CO_2 from high-pressure pipeline into low-pressure field**
- Safe storage
  - Well integrity maintained during operations

    Injection on – off: temperature cycling in well

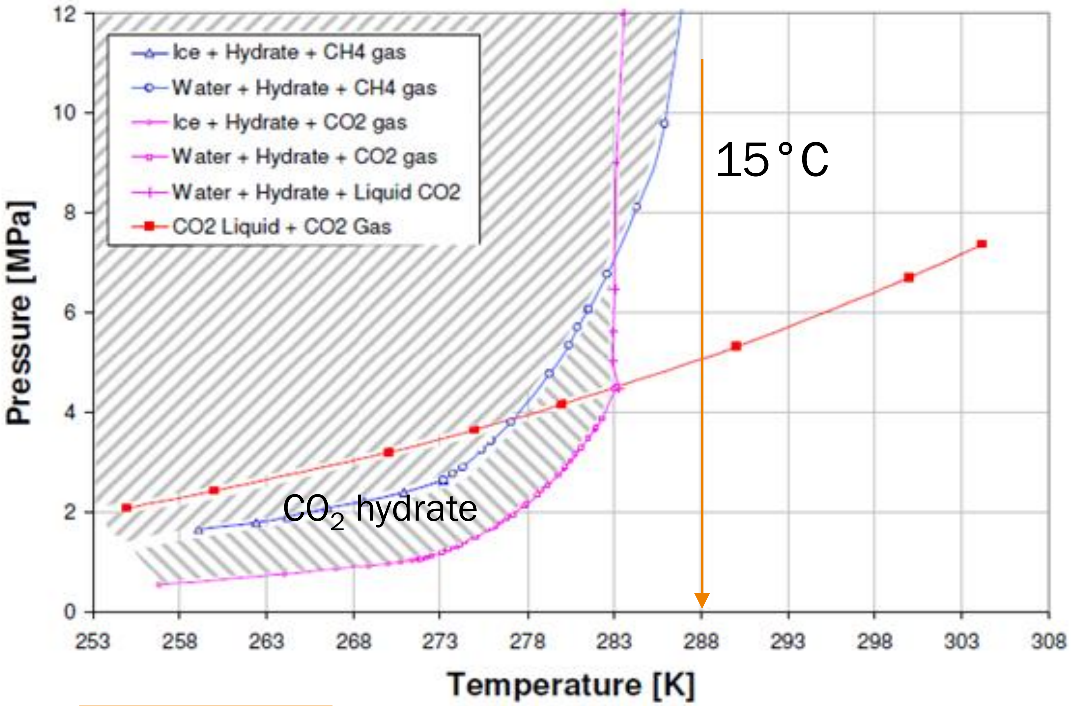
    Assume: **Wellhead: T > -10°C** (materials constraint)
- Reservoir and cap rock integrity preserved

  Large contrast temperature CO_2 – reservoir

  Thermal stress on top of **injection pressure**

  Needs specific simulations
- Maintain operability of reservoir
  - Avoid salt deposition and hydrate formation
  - Hydrates: bottomhole T > 15°C
- Flow rates through well: limits due to erosion, vibration (*not included here*)

For downhole temperature above about 15°C, CO_2 hydrates unlikely to occur



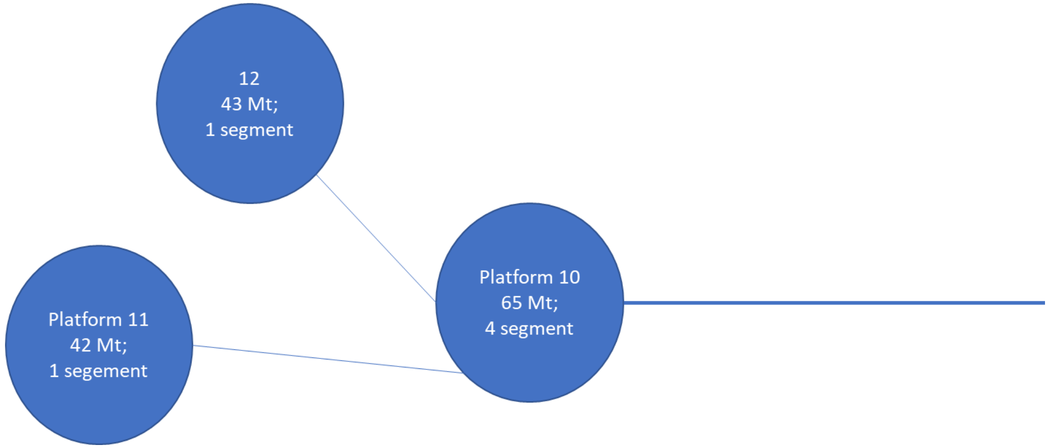
Need water…

CLUSTER OF FIELDS
HIGH-QUALITY RESERVOIRS

- Cluster of three platforms, 18 wells
  - Six reservoirs / compartments
  - High injectivity (good quality wells)

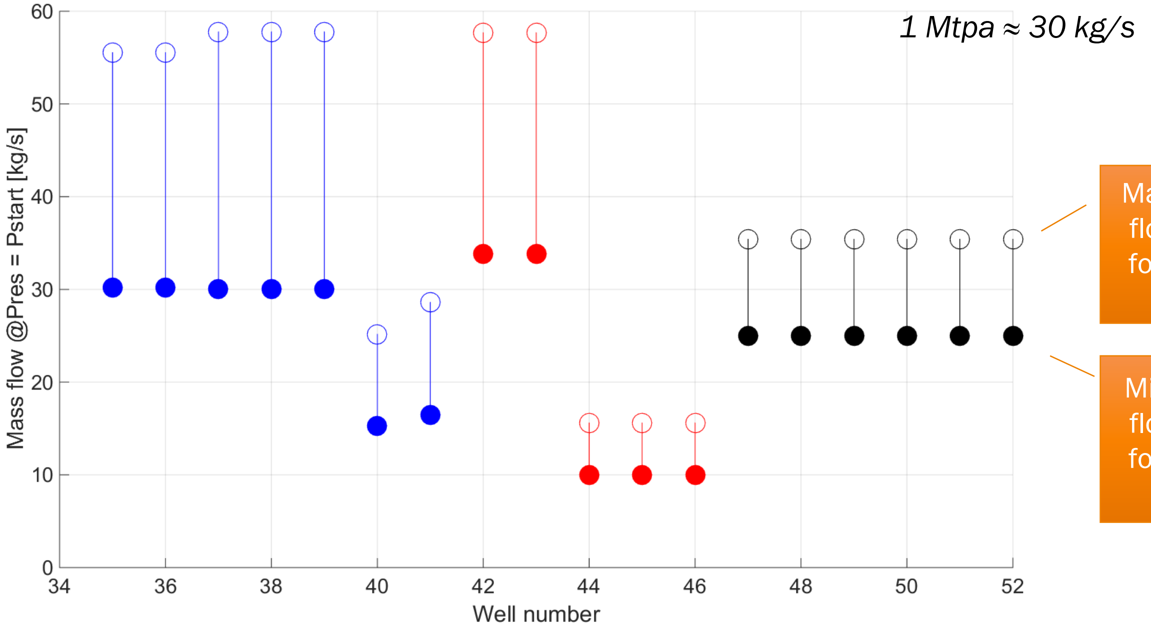
- Injection rates (during first phase of injection)
  - High steady-state rates for most wells (liquid CO_2!)
  - *Minimum* flow of about 1 Mtpa for some wells

- At cluster level (combining all wells)
  - Few wells needed to reach multi-megatonne (Mtpa) rates
  - Limited flexibility: stable supply required


12
43 Mt;
1 segment

Platform 10
65 Mt;
4 segment

Platform 11
42 Mt;
1 segement

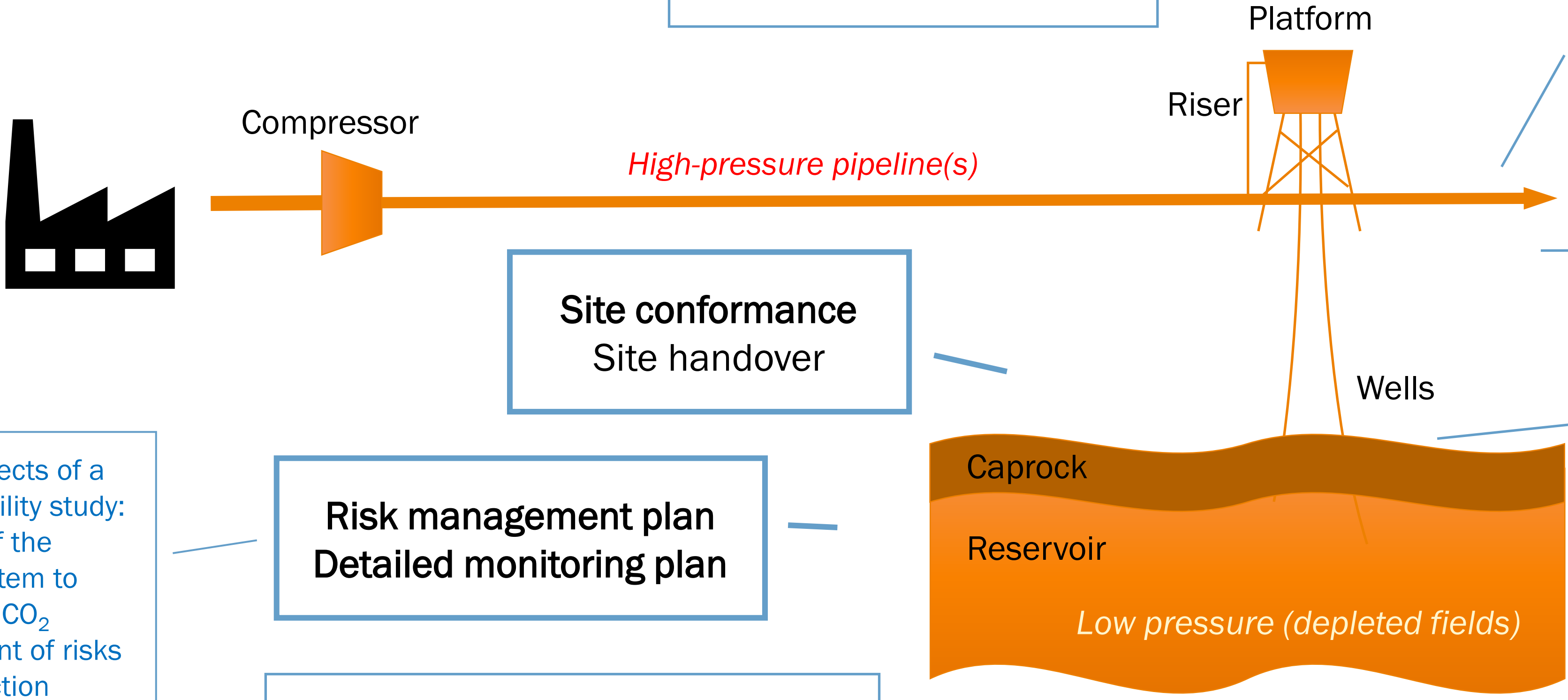


1 Mtpa ≈ 30 kg/s

Maximum flow rate for liquid CO_2

Minimum flow rate for liquid CO_2

CO$_2$ STORAGE PROJECT



Re-using platforms, wells, pipelines

Transport network development - flexibility, robustness

Large pressure drops in system – management of CO$_2$ temperature is key element of operations

Site conformance
Site handover

Near-well and well-based processes

Covers *all* aspects of a storage feasibility study:
- response of the storage system to injection of CO$_2$
- management of risks during injection

Risk management plan
Detailed monitoring plan

Well integrity, fault stability, flow rates, intermittency, low-temperature cycling, …

Pressure and temperature distribution and development in reservoir (injected CO$_2$ is cold!)

CO_2 STORAGE IN DEPLETED FIELDS
STORAGE PROJECT DEVELOPMENT

- The case of depleted fields typical for the Dutch offshore:
  - Most gas accumulations are in fault blocks with limited aquifer support
  - Many (not all) are produced to (very) low depletion pressure

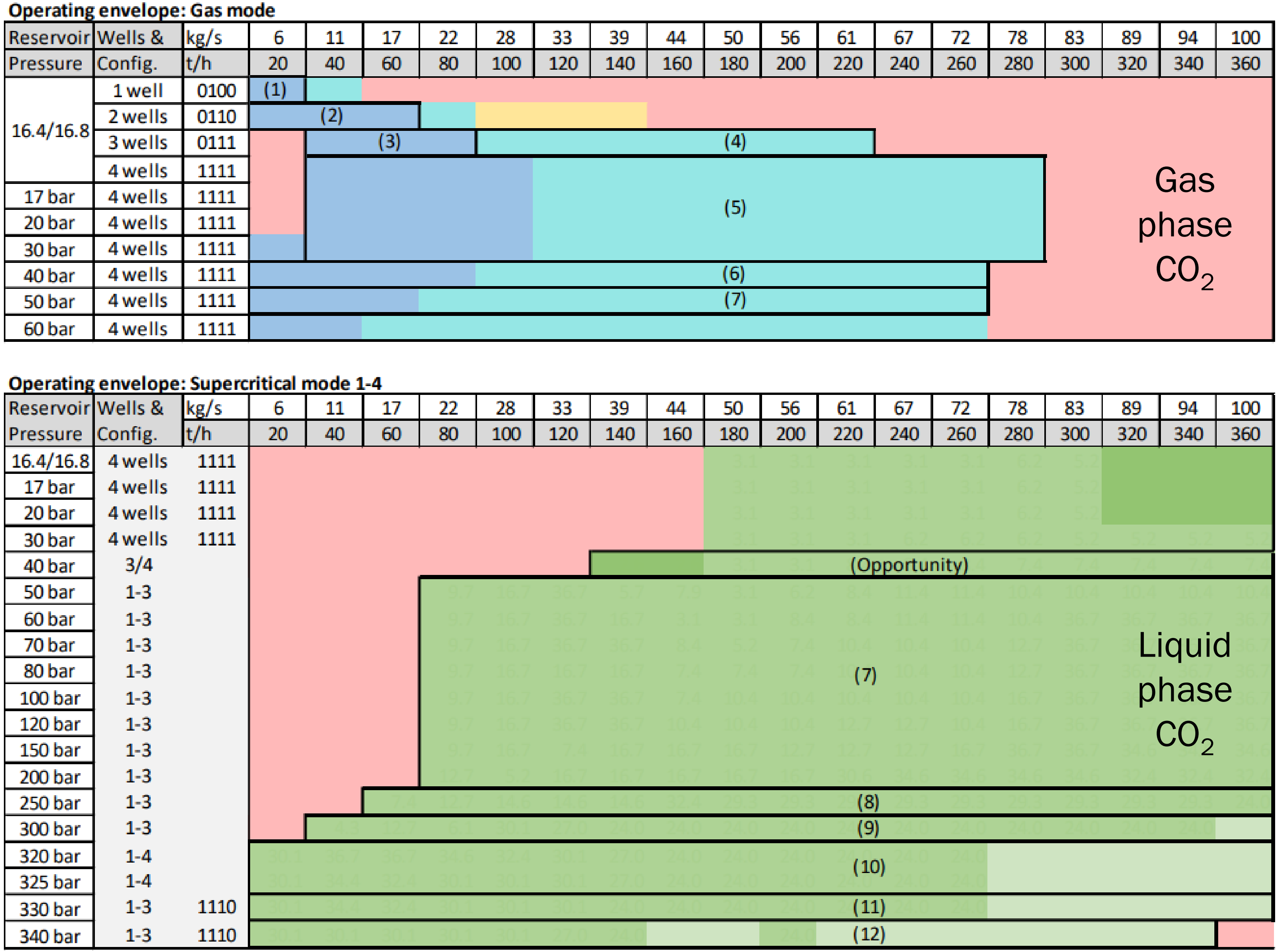
  → This leads to challenges for the safe injection of CO_2 from vessels or high-pressure transport lines

- Goal of storage feasibility study: develop a depleted field as a CO_2 store:
  1. Define the engineering limits for (parts of) the storage system (pipeline, wells) and the relation between engineering choices and storage-related and operations-related risks
  2. Select the best design or design concept ('best': one or more targets such as lowest cost, highest rates, lowest risks, inclusion in existing CCS infrastructure (if relevant))

     (Design concept: e.g., low-p or high-p transport, well count, single / multiple tubing, etc.)
  3. Study, in detail, the steady-state and transient conditions in the injection and storage system: define operational windows of the wells, the reservoir and the overall system – under the requirements of ALARP containment and operational risks
  4. A revisit of '2' may be required during '3'

PORTHOS
INJECTION PLAN

- High-level plan for the operational window of the three depleted fields, four wells, over the lifetime of injection
- Approach chosen:
  - Gas phase at start
  - Liquid CO_2 later
- Alternative:
  - Liquid from start
  - Not feasible: supply limitations



Operating envelope: Gas mode

Reservoir Pressure	Wells & Config.		kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
			t/h	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
16.4/16.8	1 well	0100		(1)																	
	2 wells	0110			(2)																
	3 wells	0111				(3)						(4)									
	4 wells	1111																			
17 bar	4 wells	1111																		Gas phase CO_2	
20 bar	4 wells	1111										(5)									
30 bar	4 wells	1111																			
40 bar	4 wells	1111										(6)									
50 bar	4 wells	1111										(7)									
60 bar	4 wells	1111																			

Operating envelope: Supercritical mode 1-4

Reservoir Pressure	Wells & Config.		kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
			t/h	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
16.4/16.8	4 wells	1111																			
17 bar	4 wells	1111																			
20 bar	4 wells	1111																			
30 bar	4 wells	1111																			
40 bar	3/4														(Opportunity)						
50 bar	1-3																				
60 bar	1-3																				
70 bar	1-3																			Liquid phase CO_2	
80 bar	1-3													(7)							
100 bar	1-3																				
120 bar	1-3																				
150 bar	1-3																				
200 bar	1-3																				
250 bar	1-3													(8)							
300 bar	1-3													(9)							
320 bar	1-4													(10)							
325 bar	1-4																				
330 bar	1-3	1110												(11)							
340 bar	1-3	1110												(12)							

Colour code:

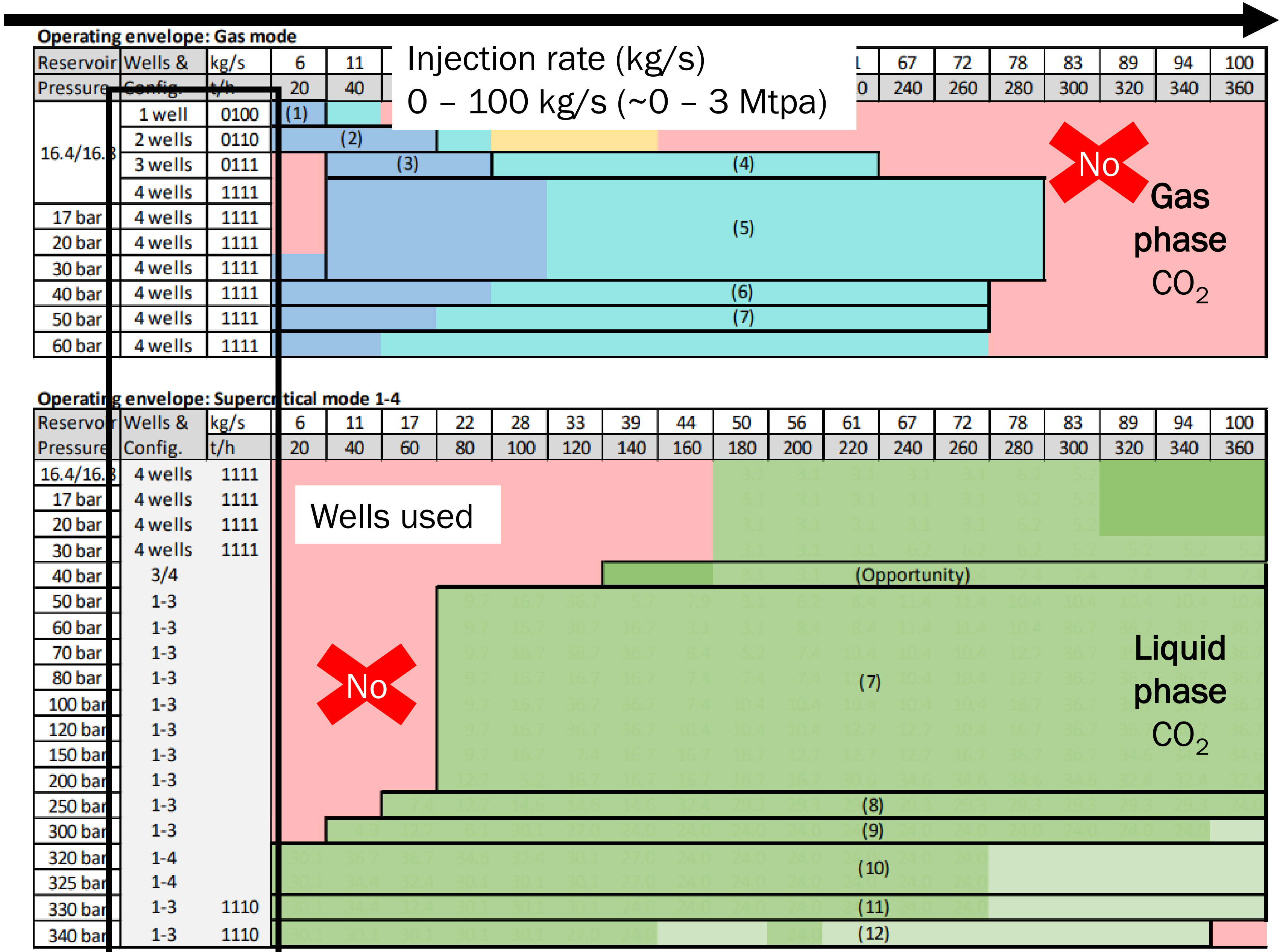
🟥	No operation possible.
🟦	Bypass mode: No compressor required.
🟦	Gas mode: Compressor required.
🟩	Supercritical mode: Inlet HP pipeline temperature = 80°C, Manifold Pressure = 85bar
🟩	Supercritical mode: Inlet HP pipeline temperature 40-80°C, Manifold pressure 85-120bar
🟩	Supercritical mode: Inlet HP pipeline temperature = 40°C, Manifold Pressure = 120bar

PORTHOS
INJECTION PLAN

No

No safe injection

Reservoir pressure (bar)
17 – 350 bar
Time
0 – 15 years



Injection rate (kg/s)
0 – 100 kg/s (~0 – 3 Mtpa)

Operating envelope: Gas mode

Reservoir	Wells &	kg/s	6	11										67	72	78	83	89	94	100
Pressure	Config.	t/h	20	40										240	260	280	300	320	340	360
16.4/16.8	1 well	0100	(1)																	
	2 wells	0110		(2)																
	3 wells	0111			(3)					(4)										
	4 wells	1111								(5)										
17 bar	4 wells	1111																		
20 bar	4 wells	1111																		
30 bar	4 wells	1111																		
40 bar	4 wells	1111								(6)										
50 bar	4 wells	1111								(7)										
60 bar	4 wells	1111																		

No

Gas phase CO_2

Operating envelope: Supercritical mode 1-4

Reservoir	Wells &	kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
Pressure	Config.	t/h	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
16.4/16.8	4 wells	1111																		
17 bar	4 wells	1111																		
20 bar	4 wells	1111																		
30 bar	4 wells	1111																		
40 bar	3/4													(Opportunity)						
50 bar	1-3												(7)							
60 bar	1-3																			
70 bar	1-3																			
80 bar	1-3																			
100 bar	1-3																			
120 bar	1-3																			
150 bar	1-3																			
200 bar	1-3																			
250 bar	1-3												(8)							
300 bar	1-3												(9)							
320 bar	1-4												(10)							
325 bar	1-4																			
330 bar	1-3	1110											(11)							
340 bar	1-3	1110											(12)							

Wells used

No

Liquid phase CO_2

Colour code:

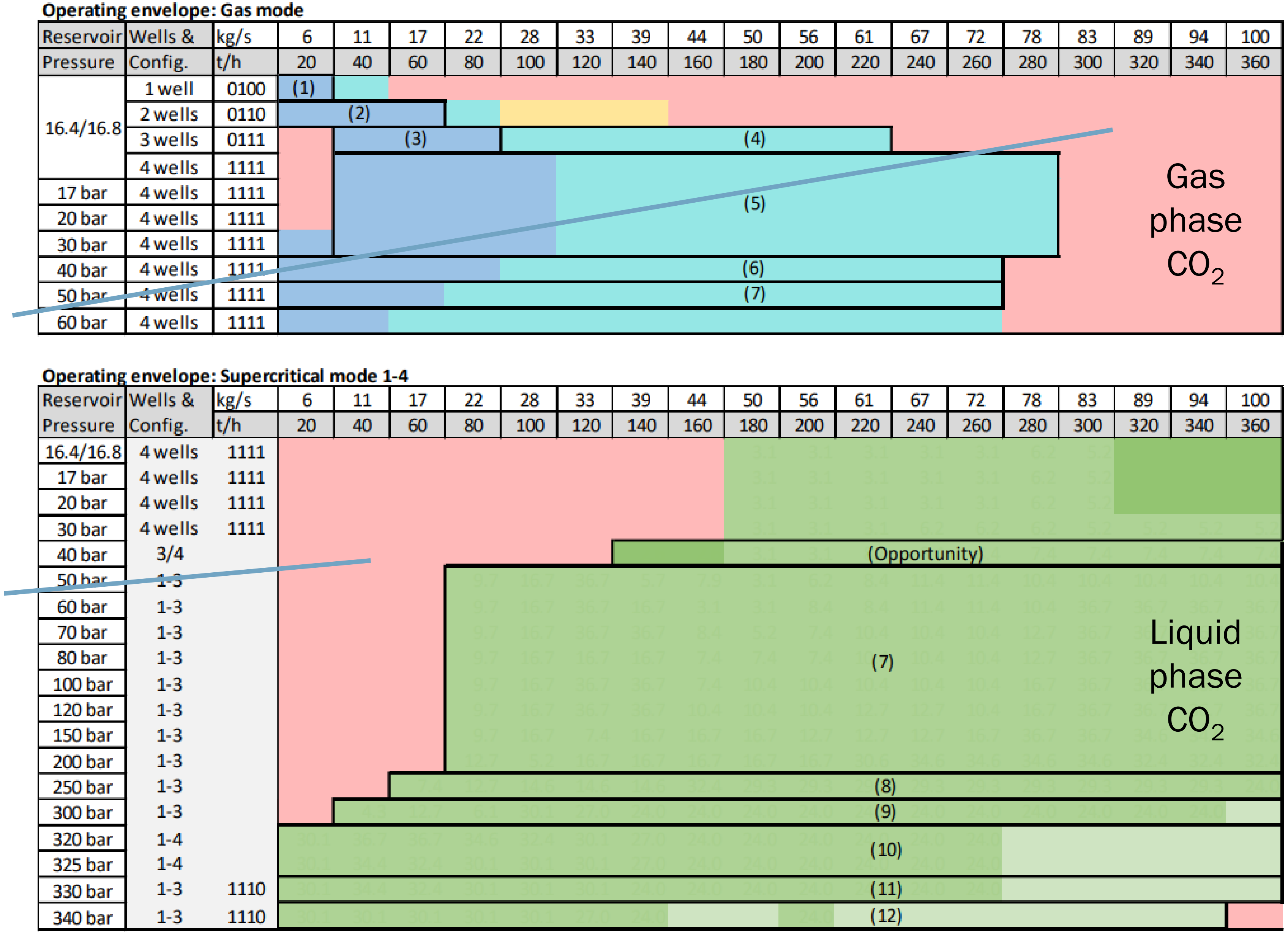
🟥	No operation possible.
🟦	Bypass mode: No compressor required.
🟦	Gas mode: Compressor required.
🟩	Supercritical mode: Inlet HP pipeline temperature = 80°C, Manifold Pressure = 85bar
🟩	Supercritical mode: Inlet HP pipeline temperature 40-80°C, Manifold pressure 85-120bar
🟩	Supercritical mode: Inlet HP pipeline temperature = 40°C, Manifold Pressure = 120bar

PORTHOS
INJECTION PLAN

No operation: too low pipeline pressure + CO_2 in gas phase: no injection

No operation: low flow rate + high-p CO_2 at wellhead + low reservoir p: too low T in well

Wells have <u>minimum</u> rate!



Operating envelope: Gas mode

Reservoir Pressure	Wells & Config.	kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
		t/h	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
16.4/16.8	1 well	0100	(1)																	
	2 wells	0110		(2)																
	3 wells	0111			(3)						(4)									
	4 wells	1111																		
17 bar	4 wells	1111									(5)									
20 bar	4 wells	1111																		
30 bar	4 wells	1111																		
40 bar	4 wells	1111									(6)									
50 bar	4 wells	1111									(7)									
60 bar	4 wells	1111																		

Gas phase CO_2

Operating envelope: Supercritical mode 1-4

Reservoir Pressure	Wells & Config.	kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
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70 bar	1-3																			
80 bar	1-3											(7)								
100 bar	1-3																			
120 bar	1-3																			
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300 bar	1-3											(9)								
320 bar	1-4											(10)								
325 bar	1-4																			
330 bar	1-3	1110											(11)							
340 bar	1-3	1110											(12)							

Liquid phase CO_2

<u>Colour code:</u>

- 🟥 No operation possible.
- 🟦 Bypass mode: No compressor required.
- 🟦 Gas mode: Compressor required.
- 🟩 Supercritical mode: Inlet HP pipeline temperature = 80°C, Manifold Pressure = 85bar
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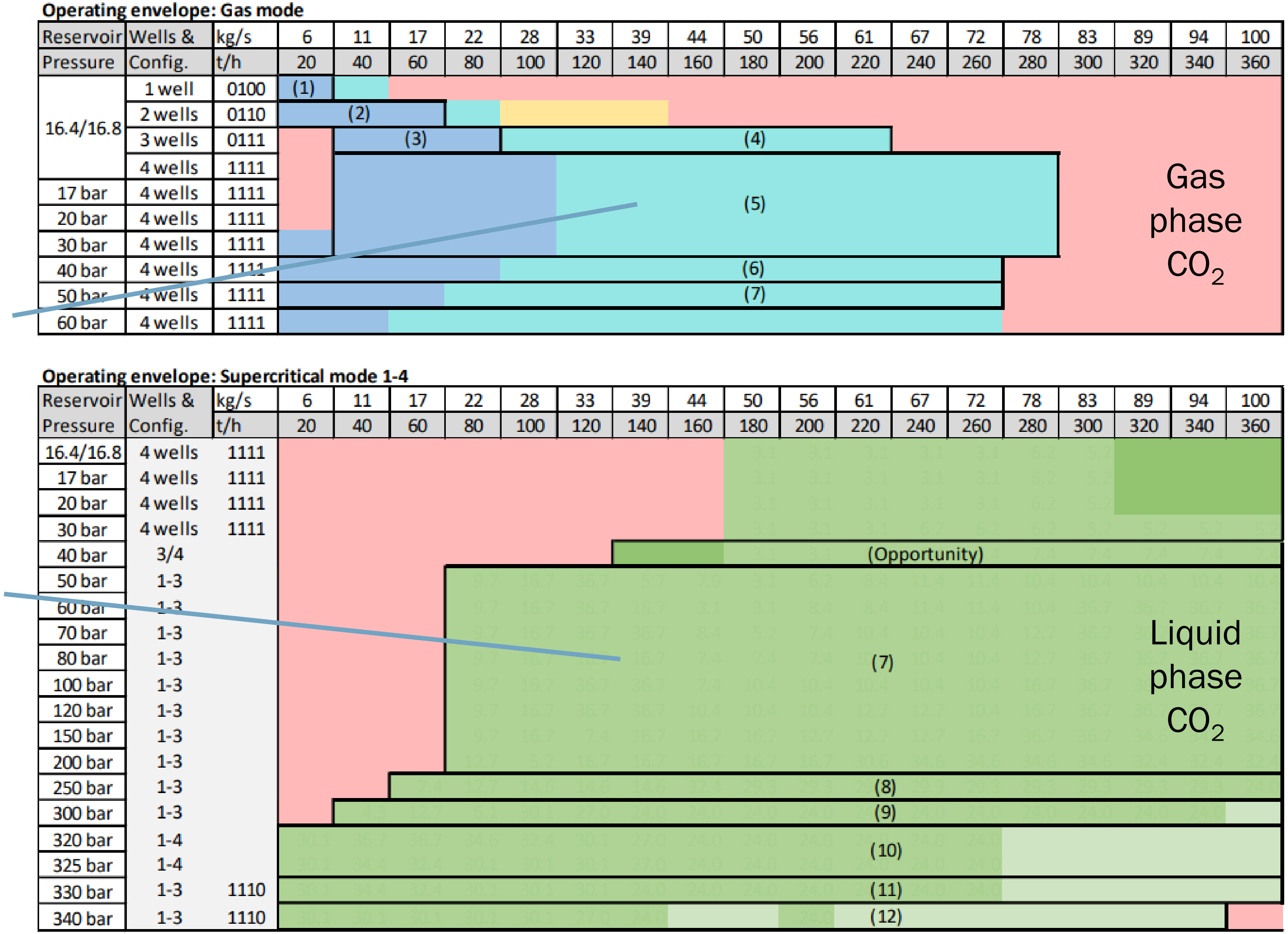
- 🟩 Supercritical mode: Inlet HP pipeline temperature = 40°C, Manifold Pressure = 120bar

PORTHOS
INJECTION PLAN

Flow rate into wells managed through pipeline pressure (slowly increasing) and pipeline temperature

Flow rate managed through supply rate (limited variation possible in pipeline conditions) and well chokes



Operating envelope: Gas mode

Reservoir Pressure	Wells & Config.		kg/s t/h	6 20	11 40	17 60	22 80	28 100	33 120	39 140	44 160	50 180	56 200	61 220	67 240	72 260	78 280	83 300	89 320	94 340	100 360
16.4/16.8	1 well	0100		(1)																	
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Operating envelope: Supercritical mode 1-4

Reservoir Pressure	Wells & Config.		kg/s t/h	6 20	11 40	17 60	22 80	28 100	33 120	39 140	44 160	50 180	56 200	61 220	67 240	72 260	78 280	83 300	89 320	94 340	100 360
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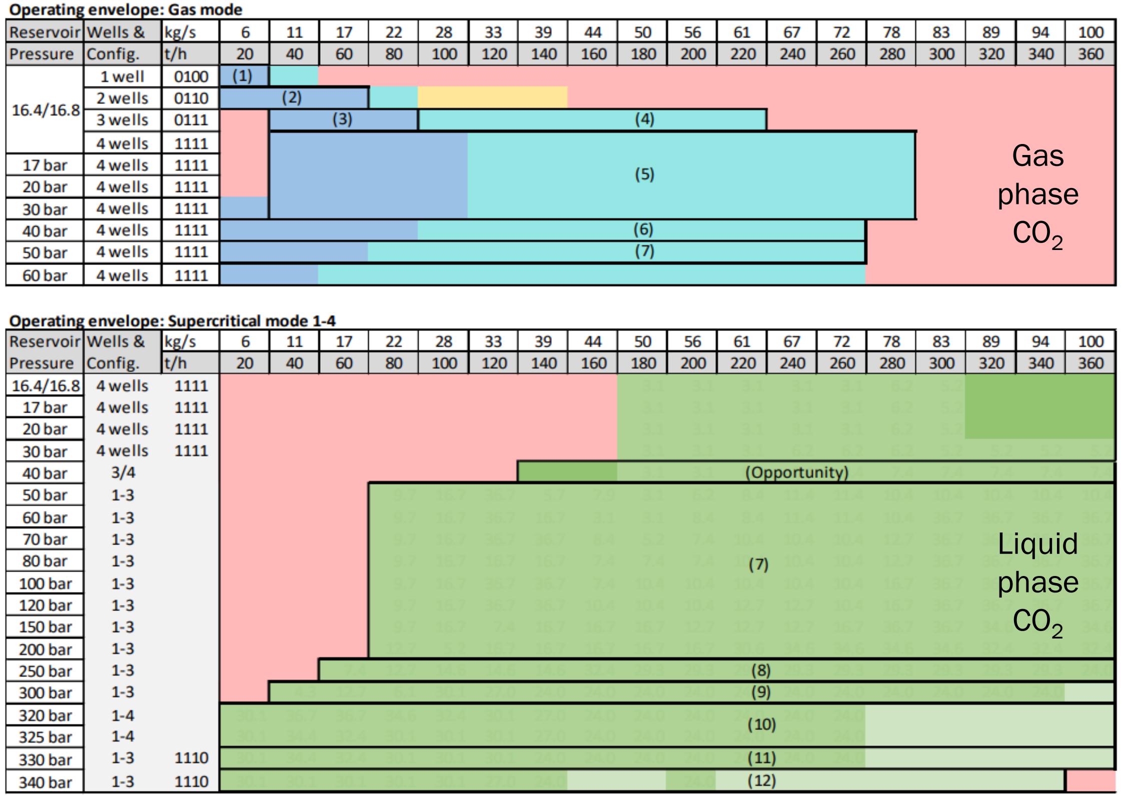
- 🟩 Supercritical mode: Inlet HP pipeline temperature 40-80°C, Manifold pressure 85-120bar
- 🟩 Supercritical mode: Inlet HP pipeline temperature = 40°C, Manifold Pressure = 120bar

PORTHOS
INJECTION PLAN

- Defining this system operational window:
  - Choice of well completions
  - Choice of pipeline design and operational mode (low-p / high-p / mixed, insulated yes/no, insulation value)
  - Continuous interaction with reservoir simulation (p and T distribution within reservoir; injection-history-dependent reservoir p at bottom wells)
  - Continuous interaction with geomechanical studies (low T may reach faults nearby the wells)
- Both steady-state (this diagram) and transient modes of operation to be analysed in detail



Operating envelope: Gas mode

Reservoir	Wells &	kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
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Gas phase CO_2

Operating envelope: Supercritical mode 1-4

Reservoir	Wells &	kg/s	6	11	17	22	28	33	39	44	50	56	61	67	72	78	83	89	94	100
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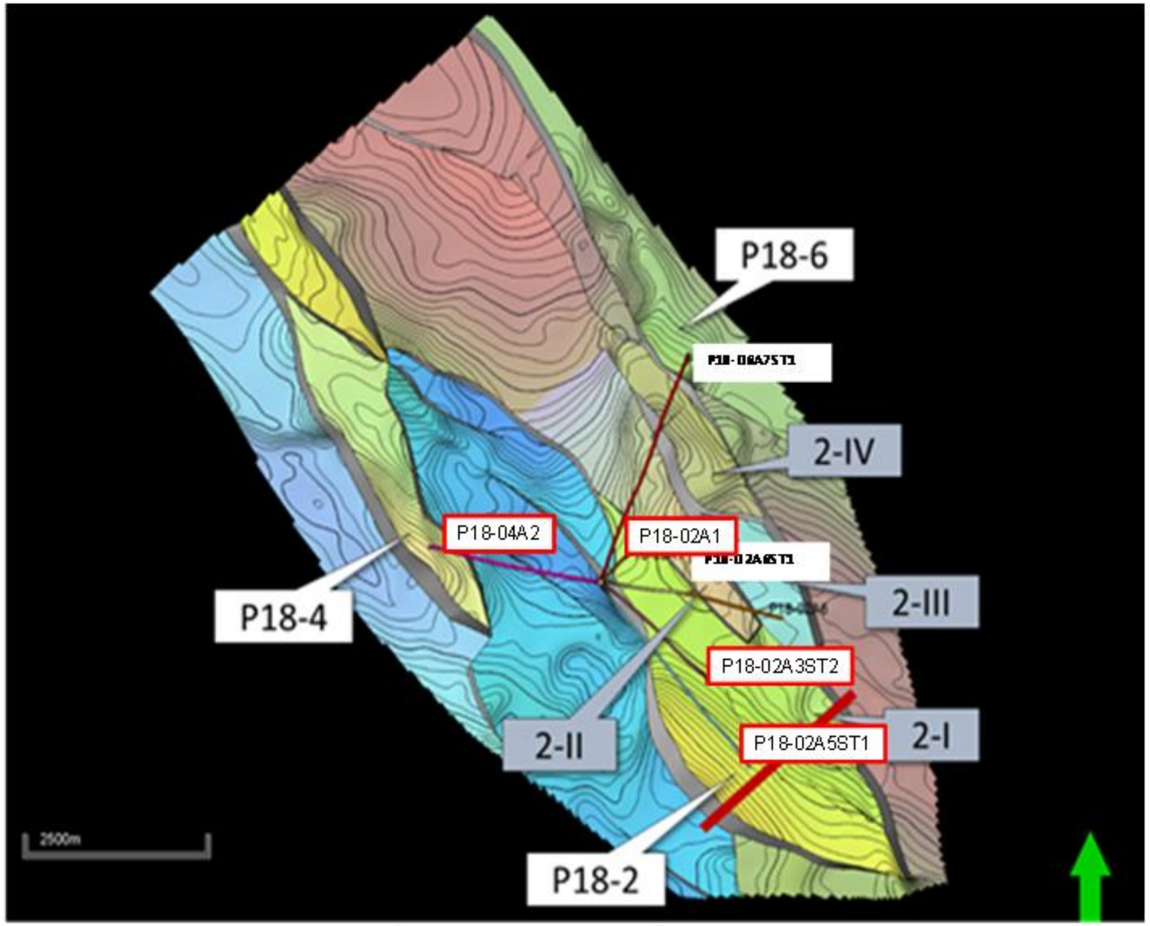
340 bar	1-3	1110											(12)							

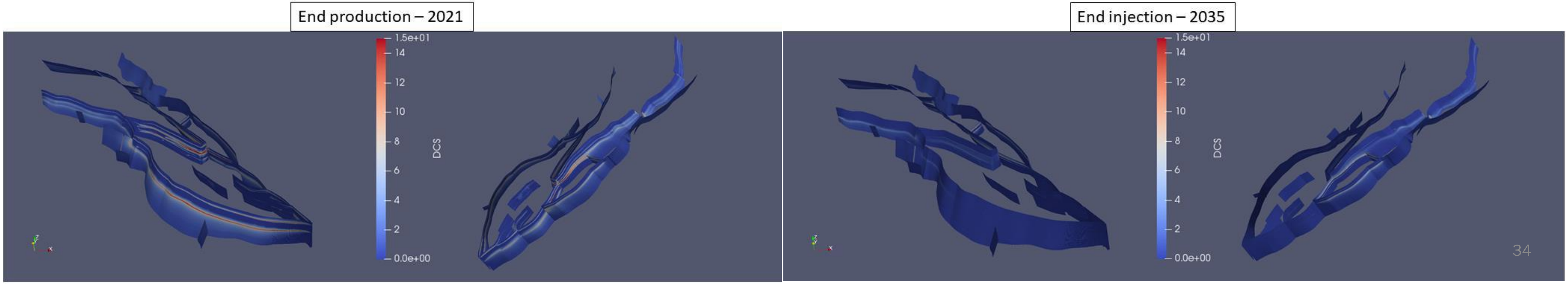
Liquid phase CO_2

PORTHOS
FAULT STABILITY

- Observation: low temperatures (ΔT ~70 °C can ingress 200-300 m into reservoir (see next slide)
- Thermal stress sufficient to activate fault in P18 fields; increasing pressure injection stabilises faults
- **Mitigation**: minimize uptime of the well P18-2A1 (closest to a fault)
- **Monitoring**: land-based seismic network, cumulative injection



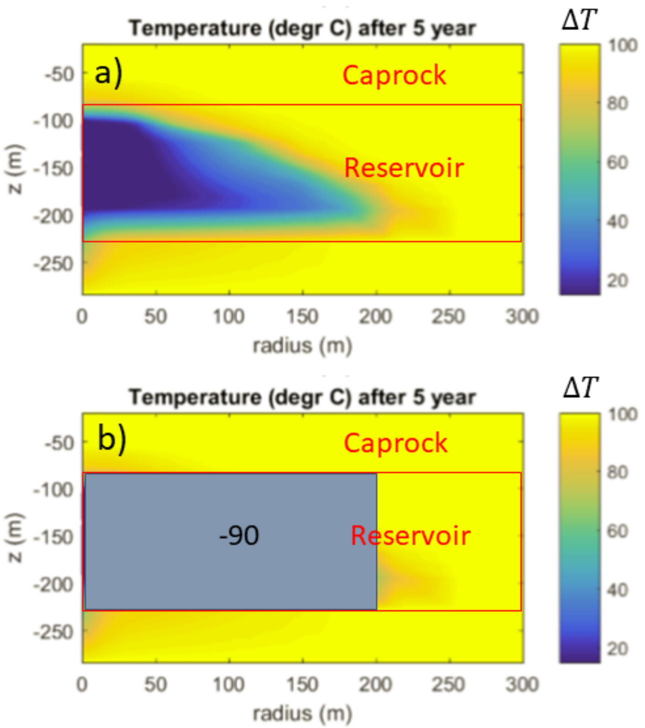
Fault shear capacity of faults in P18 system, after production (left) and after injection (right)

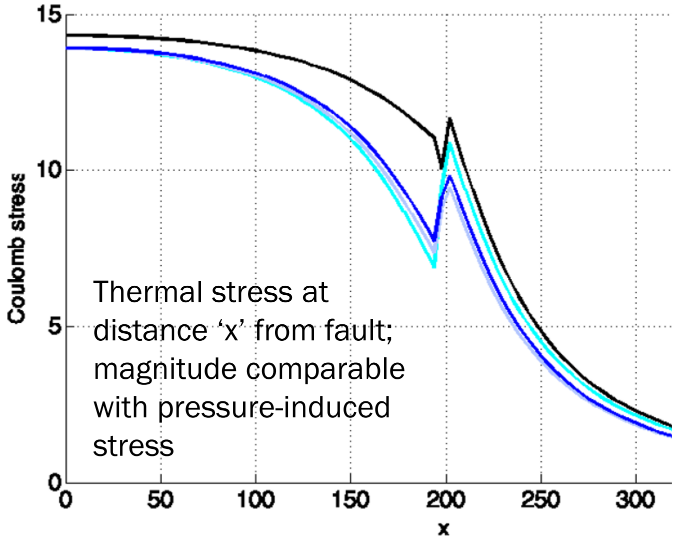

End production – 2021

End injection – 2035

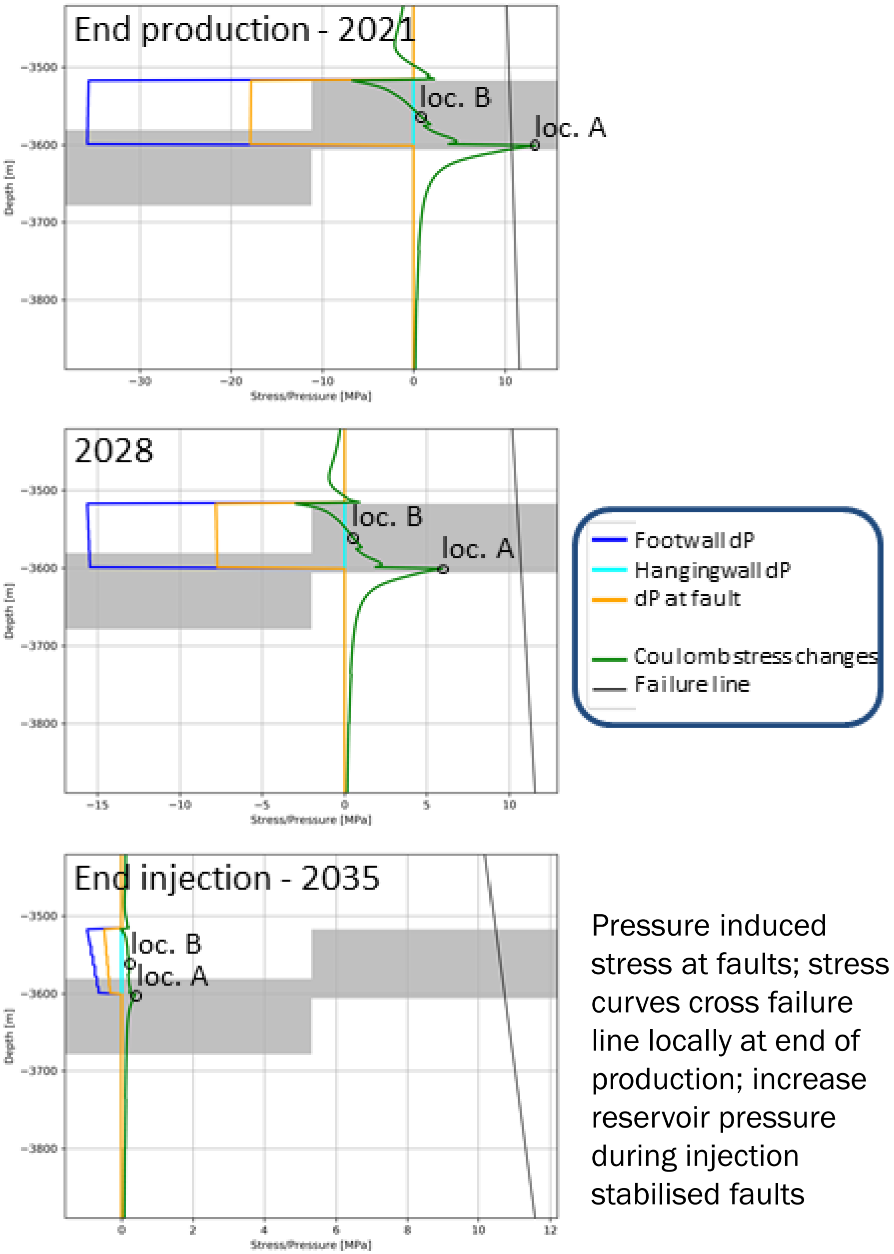
PORTHOS
FAULT STABILIITY

- Simulations show that:
  - Faults critically stresses after production
  - Increasing reservoir pressure during injectionincreased fault stability
  - Thermal stress from cold CO_2 sufficient to bring stress at faults (locally) beyond failure line
  - Low-temperature front travels 200-300 into reservoir
- Conclusions





Thermal stress at distance ‘x’ from fault; magnitude comparable with pressure-induced stress

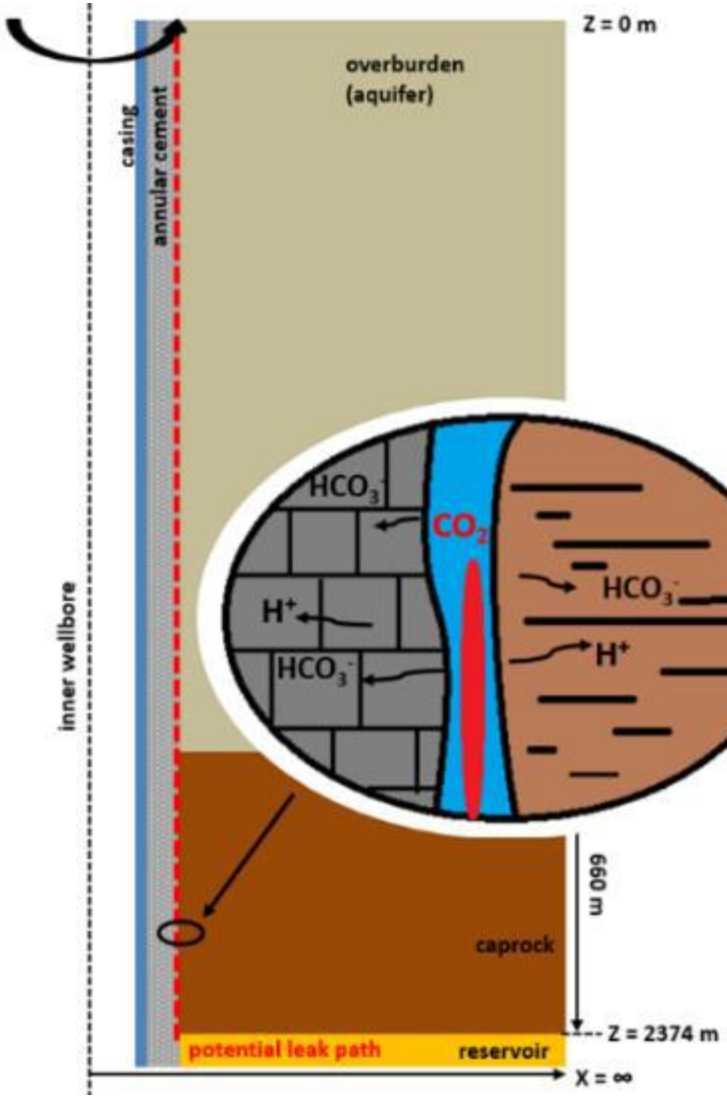


Pressure induced stress at faults; stress curves cross failure line locally at end of production; increase reservoir pressure during injection stabilised faults

PORTHOS

WELL INTEGRITY: MICRO-ANNULI

- Observation: low temperature of injected CO_2 (temperature difference is significant) is likely to create micro-annuli between cement and casing
- These could connect to form a conduit between reservoir and formations above caprock
- However:
    - Pressure in reservoir is limited to below hydrostatic: absence of driving force
    - Pressure at injection wells is above hydrostatic only during last phase of injection
    - Likelihood of continuous conduit across hundreds of meters of caprock is small
    - Worst-case estimate of CO_2 migrating through micro-annuli: only in last phase injection, *very* small volume
- Therefore:
    - Not a key risk



PORTHOS MONITORING

- Day-to-day monitoring: **p, T, q, composition**
- Logs to be run once a year, during planned shut in
- **Traffic light system** triggers additional monitoring and corrective measures
  - Threshold values to be defined after FEED; updated again after commissioning phase
- No seismics!
  - No value, unless perhaps when leakage is detected (not mentioned in license application)

Parameter / purpose	Where	How	Pre	Injection	Post-cl	Post-ab
Flow into wells, CO_2 in reservoir	Wells	P, T, q, DTS		Cont.		
Composition	Along CCS system	Various		Cont.		
Casing integrity	Wells	CBL/USIT	Once			Once
Tubing integrity	Wells	DTS	Cont.	Cont.	Cont.	
Annulus p	Wells		Cont.	Cont.	Cont.	
Micro-annuli	Wells	USIT	Once			Once
		DTS / DAS	Once	Once/yr	Twice/yr	Once
CO_2 emissions	Platform	Various		Discont.		
Seabed bubbles	Near platform	ROV	Once	Once /2 yr	Once /2 yr	Once /2 yr
Seawater sample	Near platform		Contin.	Contin.	Contin.	Contin.
Pockmarks	Near platform	Sonar	Contin.	Contin.	Contin.	Contin.
Seismicity			Cont.	Cont.	Cont.	Cont.

Cont = continuous; Contin = contingency
Simplified table!

PORTHOS – FIRST CCS PROJECT IN NETHERLANDS
CONCLUSIONS

- Storage capacity 1.7 Gt in offshore depleted gas fields
- Porthos project: developing a cluster of three gas fields in the P18 block
  - Short distance to shore: allows first phase of gas phase injection, before injection in liquid phase
- Shell, TotalEnergies, Neptune Energy: developing depleted fields for storage
  - Further from shore: injection more challenging during period of low reservoir pressure
  - Development of transport & storage network

- Next activities
  - Porthos:

    Financial investment decision (FID), expected early 2023

    FEED, construction, commissioning (2023 – 2025), start injection (2025/2026)
  - Shell, TotalEnergies, Neptune Energy: start injection 1 – 3 years later
  - *… and, of course: close cooperation (interoperability!) with nearby transport and storage projects (Denmark, UK, Norway)*

PORTHOS – FIRST CCS PROJECT IN NETHERLANDS
WAY AHEAD

Work started on preparation for operational phase

- **Conformance assessment & MMV** – interpretation in terms of storage system performance / conformance
  - Forecasting data, back-projection of differences with measured data into geological model updates
  - Involves assessment of risks in the system
  - R&D work done in TNO; also preparing a proposal under an European R&D call (Spring 2023)
- Improve understanding of **near-well processes** (ERA-NET ACT **RETURN**, next slides)
  - Reduce uncertainty in reservoir – well coupling
- Prepare **offshore network evolution** (ERA-NET ACT **ACTION**, next slides)
  - Understand how newly developed depleted fields can be added to an ongoing T&S network
- Continue work on **re-use of gas wells for CO_2 injection** (JIP **WISCoS**)
  - Screen / workover / estimates of cost and efforts
- Set up CO_2 flow loop (TNO labs) to measure flow behaviour near chokes and valves
  - TNO flow loop operational 2024, to support operational phase of CCS projects

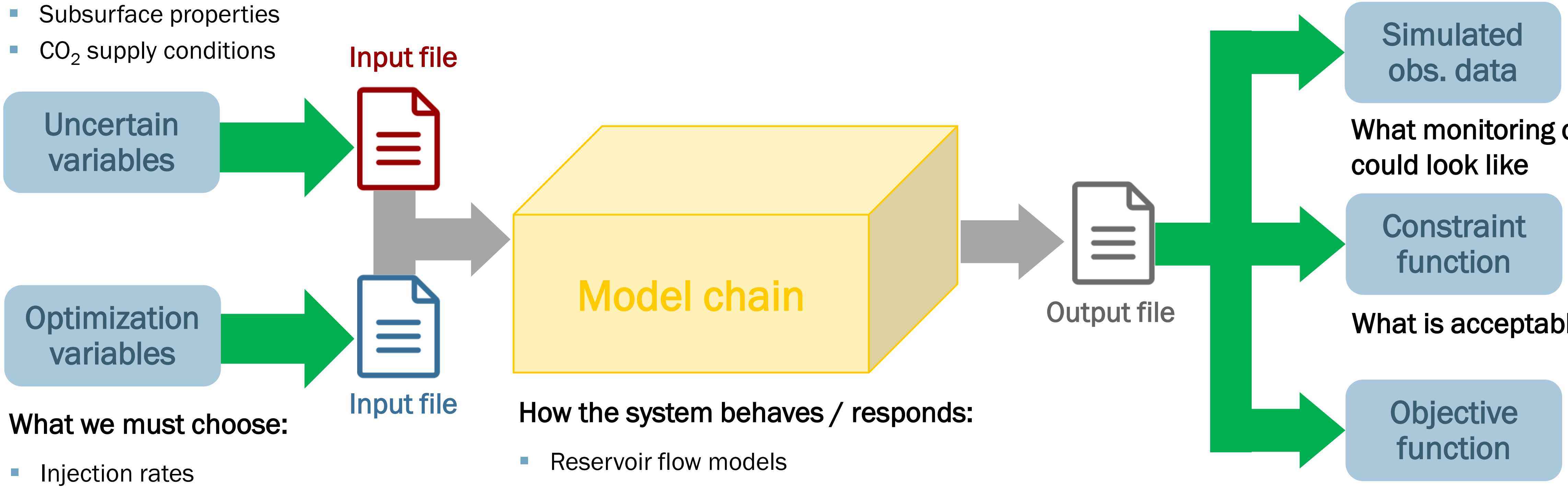
CONFORMANCE ASSESSMENT, MMV

CCS MODEL CHAIN AT THE BASIS

Starting point for CCS (and MMV) system design (pre-FEED), for conformance assessment (operational phase)

What we must be robust against:

- Subsurface properties
- CO_2 supply conditions



Input file

Uncertain variables

Optimization variables

Input file

Model chain

Output file

Simulated obs. data

What monitoring data could look like

Constraint function

What is acceptable

Objective function

What is performance

What we must choose:

- Injection rates
- Well locations
- Monitoring system

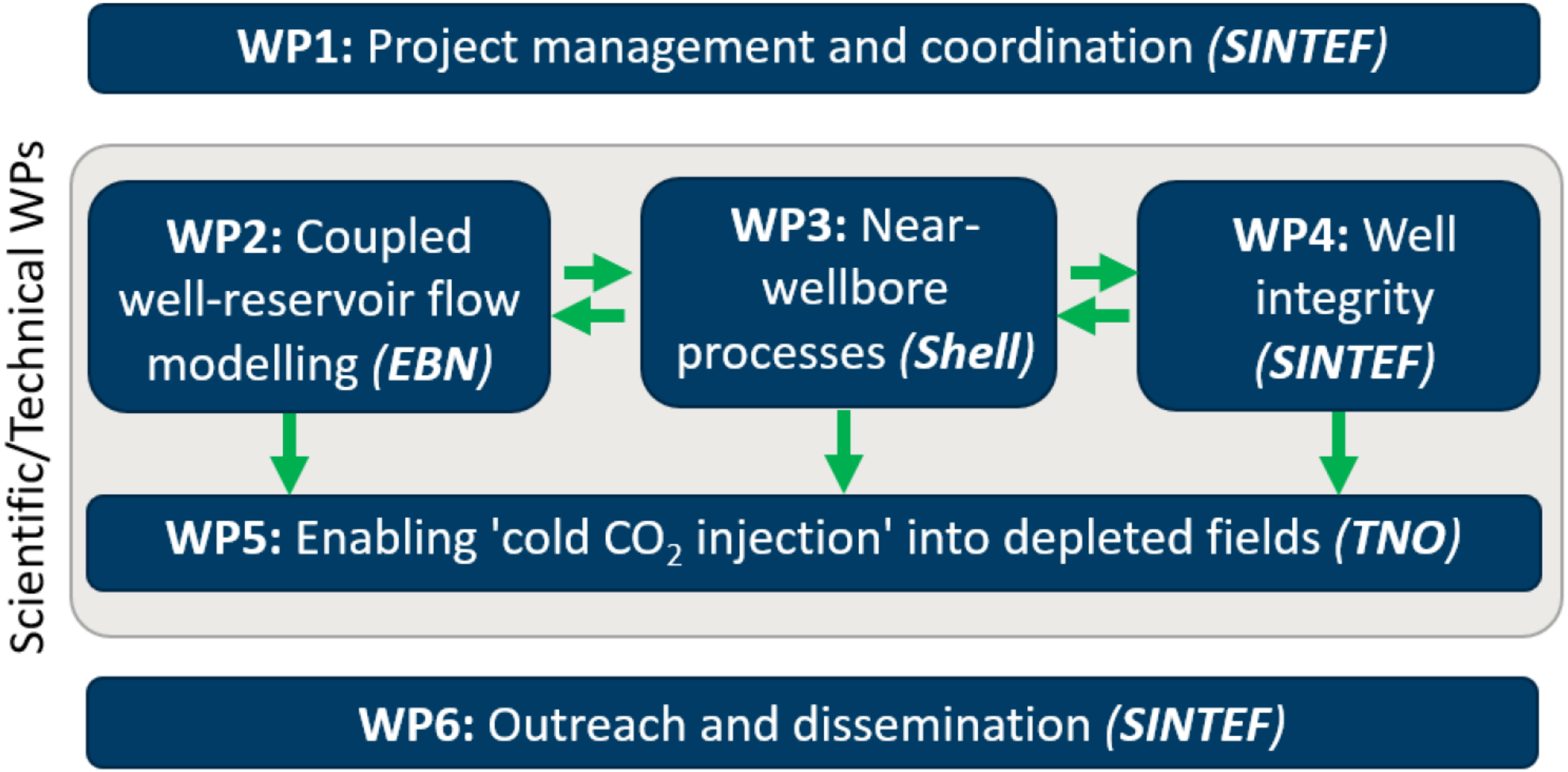
How the system behaves / responds:

- Reservoir flow models
- Geomechanical models
- Geophysical models
- Wellbore / facility network models
- Coupled solutions of the above

Barros et al. (2022)

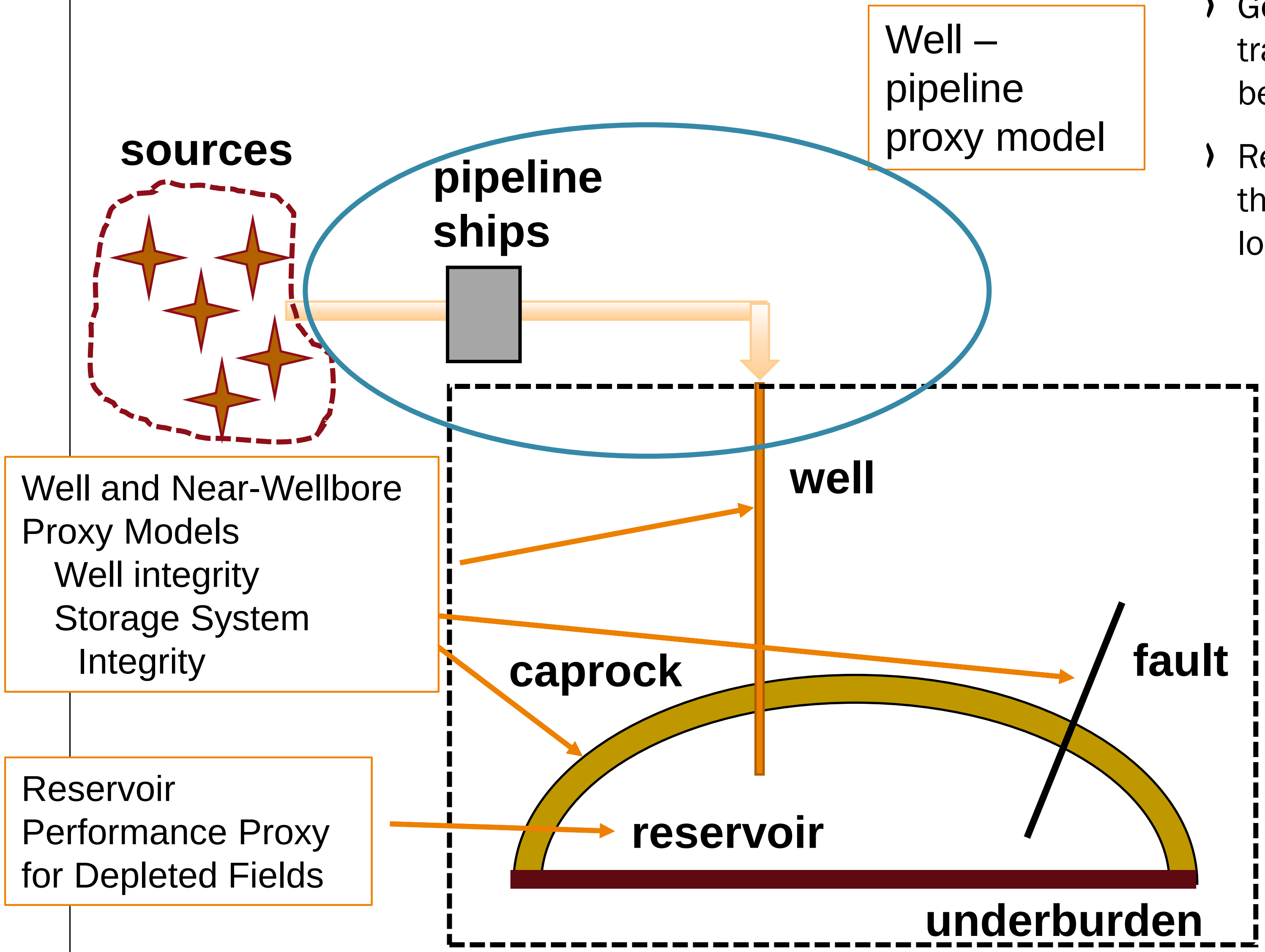
ERA-NET ACT3 'RETURN'
WELL-BASED AND NEAR-WELL PROCESSES IN DEPLETED FIELDS

- **Project started Q2 2022**
- **Duration 3 years**
- Goal: improve understanding and simulation capabilities of processes acting near injection wells in depleted fields
- Relevance: such knowledge and simulation capabilities will be needed when interpreting MMV data and assessing system conformance



ERA-NET ACT3 'ACTION'

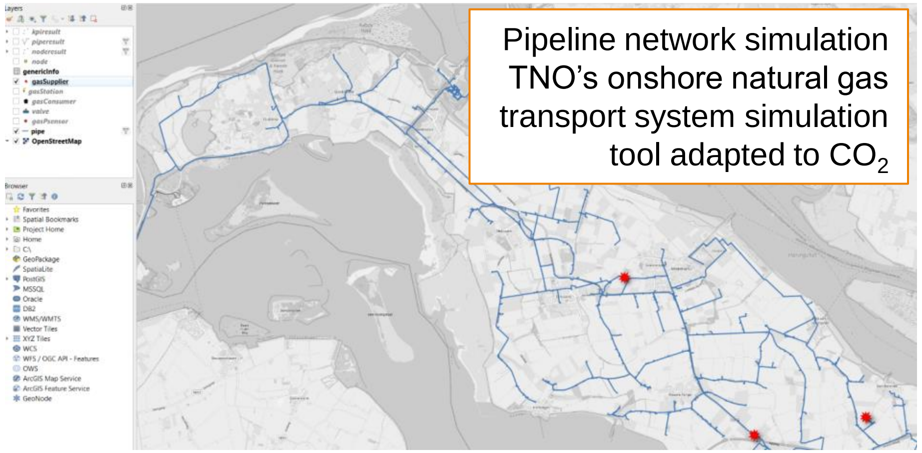
- **Project started Q2 2022**
- **Duration 3 years; lead: ICL (UK)**
- Goal: create physics-of-CO_2-flow-based simulator of a CCS transport & storage network, study a network's behaviour, management and evolution
- Relevance: the behaviour depleted fields is likely to affect the development and operation of a network of storage locations – should be clarified as early as possible



Well – pipeline proxy model

Well and Near-Wellbore Proxy Models
Well integrity
Storage System Integrity

Reservoir Performance Proxy for Depleted Fields



Pipeline network simulation
TNO's onshore natural gas transport system simulation tool adapted to CO_2

Development of CO_2 network simulator
- Depleted fields
- Network operation & evolution
- Steady-state simulation

WISCOS

CONSORTIUM OF REX-CO$_2$ FOLLOW-UP

REX-CO$_2$

TNO
wintershall dea
BGS British Geological Survey
ebn
أدنوك ADNOC

equinor
Ikon SCIENCE
Chevron
Los Alamos NATIONAL LABORATORY EST. 1943
ifp Energies nouvelles

vallourec
NEPTUNE ENERGY
ReStone AS
GUVERNUL ROMÂNIEI
iRO

SINTEF
GeoEcoMar
CO$_2$ club ROMANIA
Oil & Gas Authority
bp

WISCoS

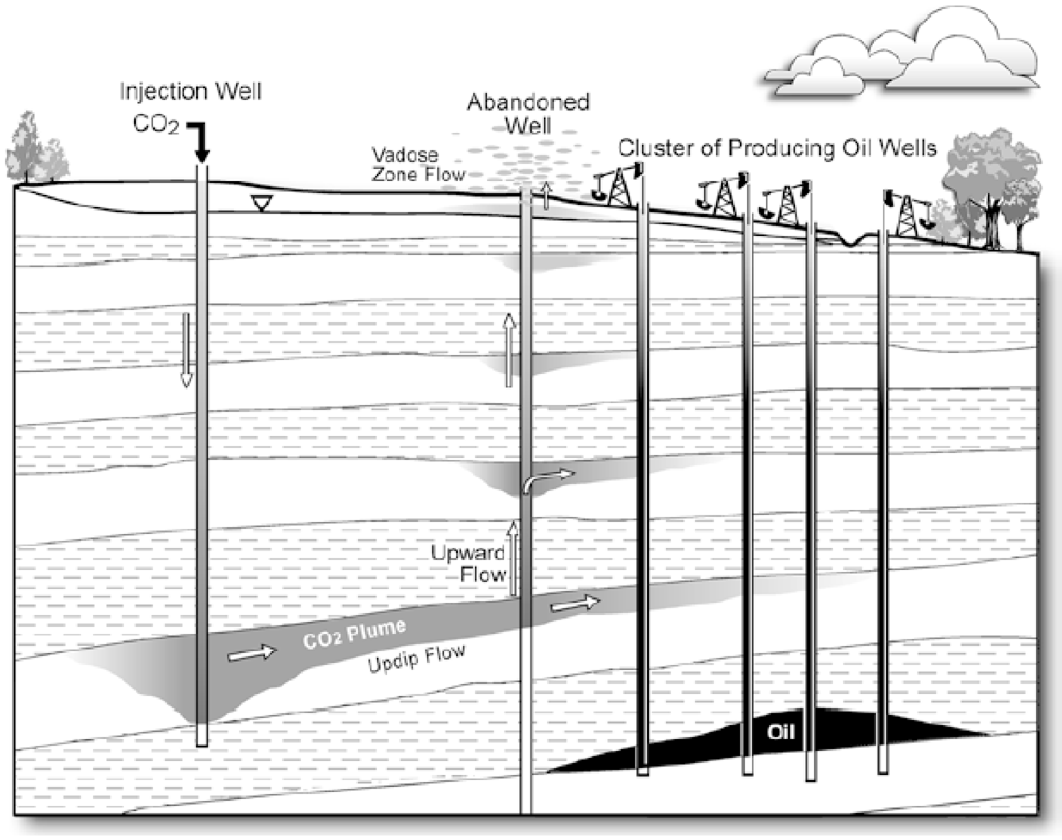
Potentially interested parties:

JIP is being set up

WISCOS

MOTIVATION / BACKGROUND

- To add value for operators and regulators in storage licence applications for maturing CCS projects, a better understanding of potential well integrity issues for each well penetrating the caprock is essential:
  - Risk-based screening
  - Quantification of key elements
  - Focussed on specific geographic location & regulatory regime



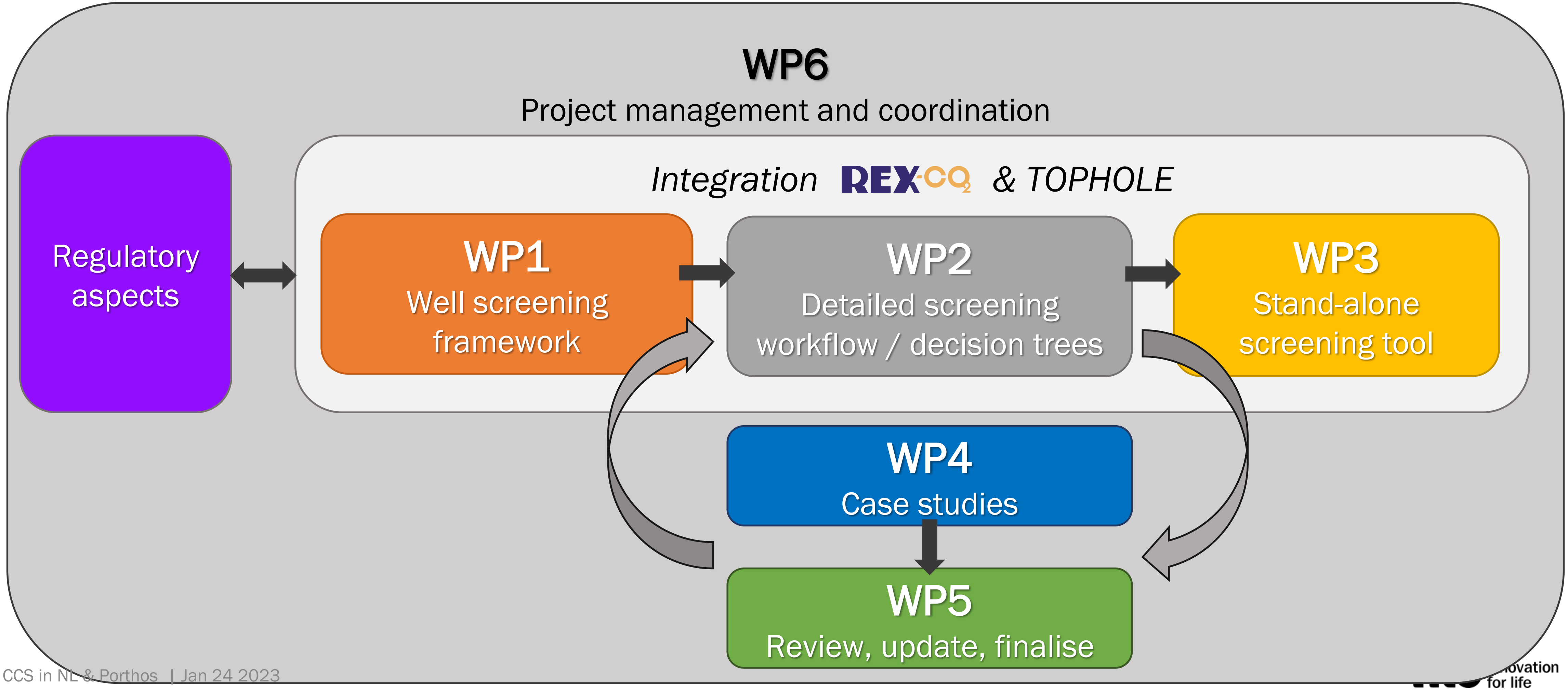
Ref.: *Gasda, Bachu and Celia, 2004*

Build upon the frameworks of REX-CO2 (i.e. re-use of wells, see https://rex-co2.eu/**) & TOPHOLE (i.e. P&A wells**, see https://www.sintef.no/en/projects/2019/tophole-monitoring-of-permanently-plugged-wells/**) to provide a complete well integrity storage screening**

WISCOS

PROPOSED PROJECT STRUCTURE

- **Objective:** to develop a new screening tool (based on previous projects) that can be used as part of the SLA within the North Sea region, identifying main opportunities and threats for CCS in the reservoir with respect to well integrity



WP6

Project management and coordination

Regulatory aspects

Integration REX-CO$_2$ *& TOPHOLE*

WP1
Well screening framework

WP2
Detailed screening workflow / decision trees

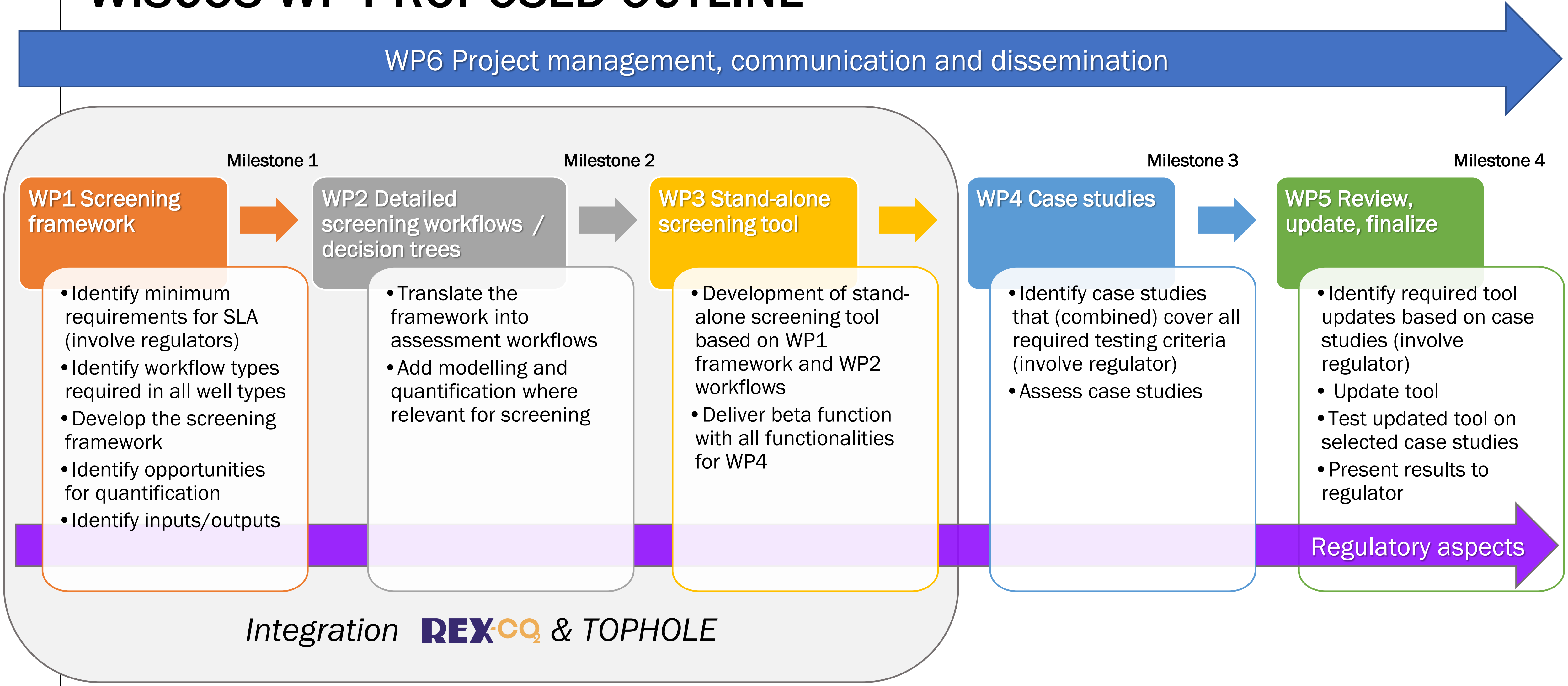
WP3
Stand-alone screening tool

WP4
Case studies

WP5
Review, update, finalise

WISCOS

WISCOS WP PROPOSED OUTLINE



WP6 Project management, communication and dissemination

Milestone 1

WP1 Screening framework

- Identify minimum requirements for SLA (involve regulators)
- Identify workflow types required in all well types
- Develop the screening framework
- Identify opportunities for quantification
- Identify inputs/outputs

Milestone 2

WP2 Detailed screening workflows / decision trees

- Translate the framework into assessment workflows
- Add modelling and quantification where relevant for screening

WP3 Stand-alone screening tool

- Development of stand-alone screening tool based on WP1 framework and WP2 workflows
- Deliver beta function with all functionalities for WP4

Milestone 3

WP4 Case studies

- Identify case studies that (combined) cover all required testing criteria (involve regulator)
- Assess case studies

Milestone 4

WP5 Review, update, finalize

- Identify required tool updates based on case studies (involve regulator)
- Update tool
- Test updated tool on selected case studies
- Present results to regulator

Regulatory aspects

Integration REX-CO$_2$ & *TOPHOLE*

WISCOS

PROPOSED END PRODUCT

- **A stand-alone software tool**
  - Independent screening framework, quantifying integrity risks where possible
  - GIS-based
  - Easy visualisation of results (i.e. plumbing diagrams, traffic light system, pdf report, etc.)
  - Linked to SLA (storage license application) activities relevant to North Sea regime

WISCOS

TIMELINE

		Date (w/c)																					
Activities	**Lead / contribute**	31-okt	7-nov	14-nov	21-nov	28-nov	5-dec	12-dec	19-dec	26-dec	2-jan	9-jan	16-jan	23-jan	30-jan	6-feb	13-feb	20-feb	27-feb	6-mrt	13-mrt	20-mrt	27-mrt
Feedback on draft proposal	All		🟧	🟧	🟧	🟧	🟧	🟧		▨	▨												
Group / consortium sessions	TNO / all partners					🟧			🟧	▨	▨	🟧		🟧		🟧							
Define technical details	TNO & WP-leads / all partners						🟧	🟧	🟧	▨	▨												
Draft full version technical proposal	TNO / all partners							🟧	🟧	▨	▨	🟧	🟧										
Draft IP&C docs (JIP agreement)	TNO								🟧	▨	▨	🟧	🟧										
Review & approve all docs	All									▨	▨			🟧	🟧	🟧							
Milestones																							
Commitment to participate	All							◆		▨	▨												
Budget agreement	All								◆	▨	▨												
JIP Consortium agreement	TNO									▨	▨						◆						
Final project proposal	All									▨	▨						◆						
Project Kick-off										▨	▨							◆					

FURTHER READING

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- ROAD CCS project close-out reports (learnings from the Rotterdam CCS project)

THANK YOU FOR YOUR TIME

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