TNO innovation for life

CO_2 transport & storage at TNO

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CATO day

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TNO GEOSCIENCES AND TECHNOLOGY

OPTIMAL USE OF THE SUBSURFACE

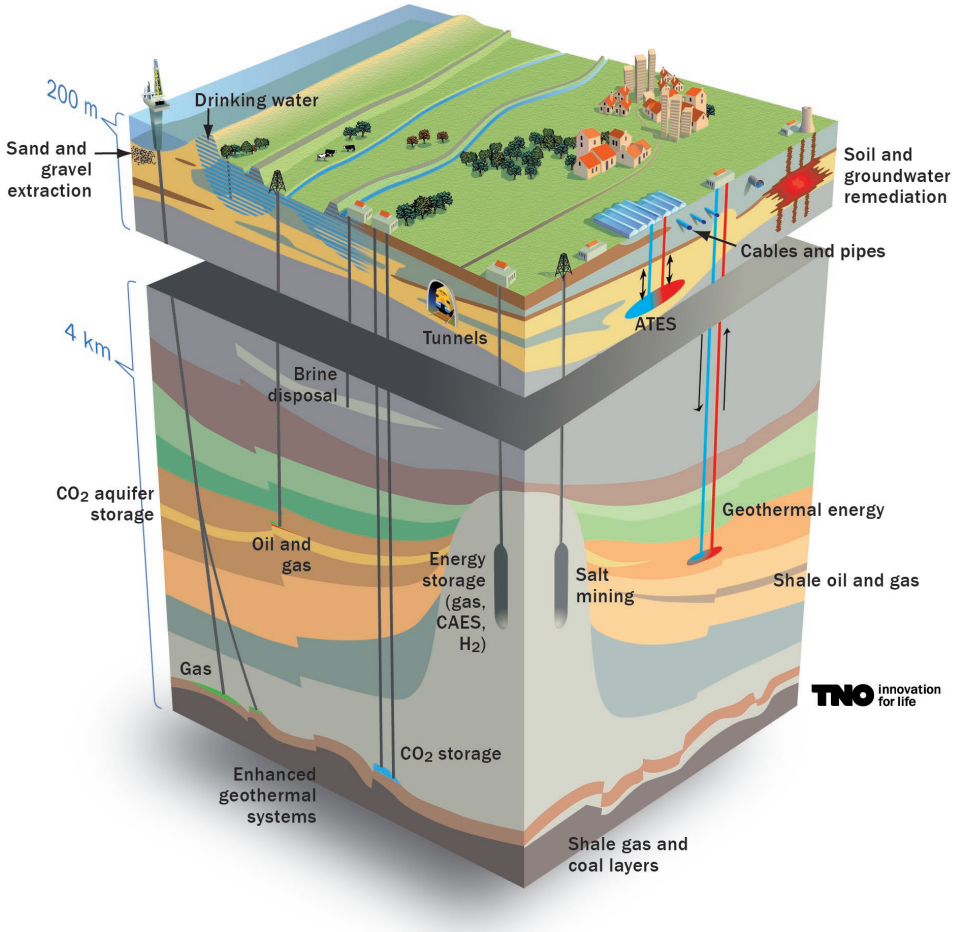
TNO → Largest R&D organisation in The Netherlands

~5000 staff, wide range of R&D topics

Unit Energy transition → Applied Geology (Dutch Geological Survey)

Mission: Energising the transition through the subsurface

- Maintain and publish data and models of the subsurface
- Advisor to the Ministry of Economic Affairs
- Exploration and appraisal for geo-energy resources, storage and buffer space
- Model and predict subsurface processes, observation and monitoring
- Optimization of complex (geo-)systems (EVEReST)

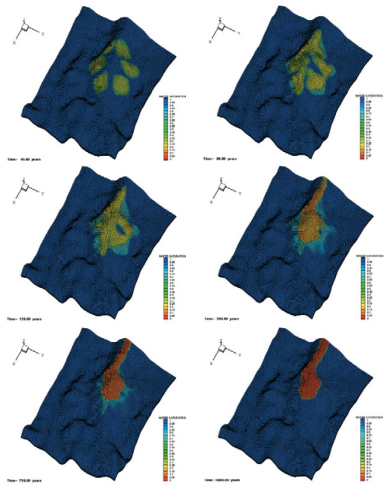


TNO HAS A STRONG TRACK RECORD ON CO_2 STORAGE

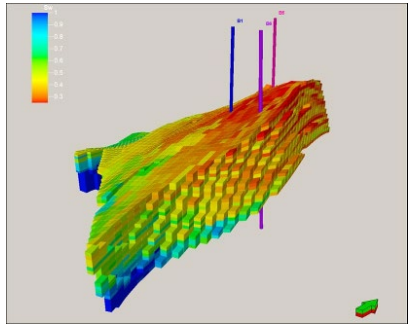
screening | feasibility | pre(feed) | construct | operations | closure | decommissioning

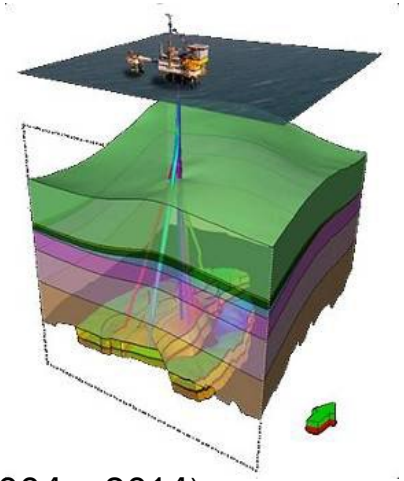
TNO has a leading role in the EU and nationally on R&D in CO_2 transport and storage. TNO's expertise covers all elements that are needed to bring a potential storage site to permit level and covers such areas as storage site characterisation, monitoring, well integrity, storage optimisation (& EOR), 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 led the CATO M€ 60 CCS R&D program in The Netherlands (2004 – 2014).

TNO has been involved in CO_2 injection (the K12-B field), developing the basis for several storage permits (for the ROAD and Porthos CO_2 projects) and designing the transport and injection system (pipelines, wells) (for the Porthos project in The Netherlands).

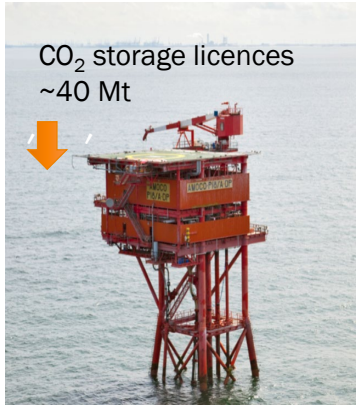


Saline formation
CO_2 storage (1990s –date)





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



Porthos – P18 cluster
(2009 – present)
CO_2 storage permits:
P18-2, P18-4

CO_2 transport and storage

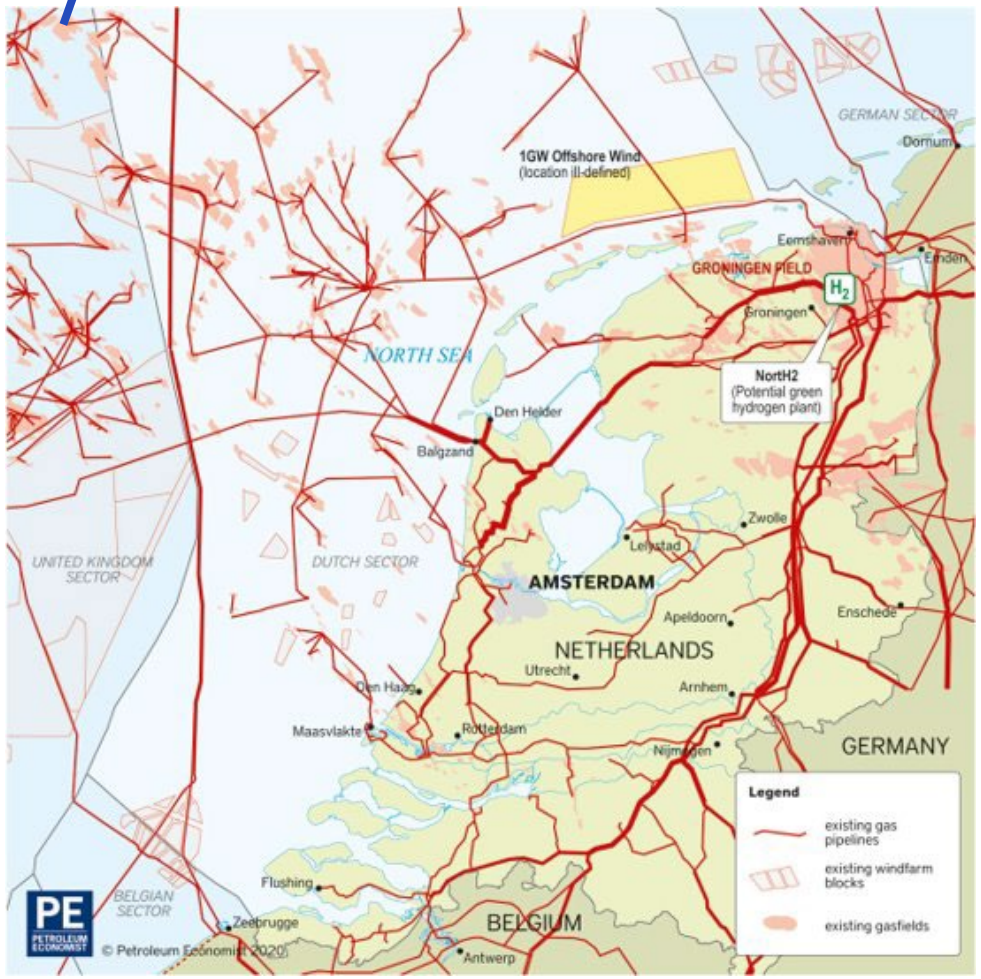
GOALS CCS IN NL

- NL government: CCS central role in strategy to meet emission reduction goals in 2030, 2050
  - Focus on offshore depleted fields
  - Development of CCS projects is market driven

- Subsidy schemes in place to support policy; examples:
  - National schemes: contract for difference
  - EU: Connecting Europe Facility (CEF): provides (partial) funding for construction of transport and/or storage infrastructure
  - EU: Innovation Fund (IF): funding for construction and operation of CCS projects

~1600 Mt storage capacity in offshore depleted fields

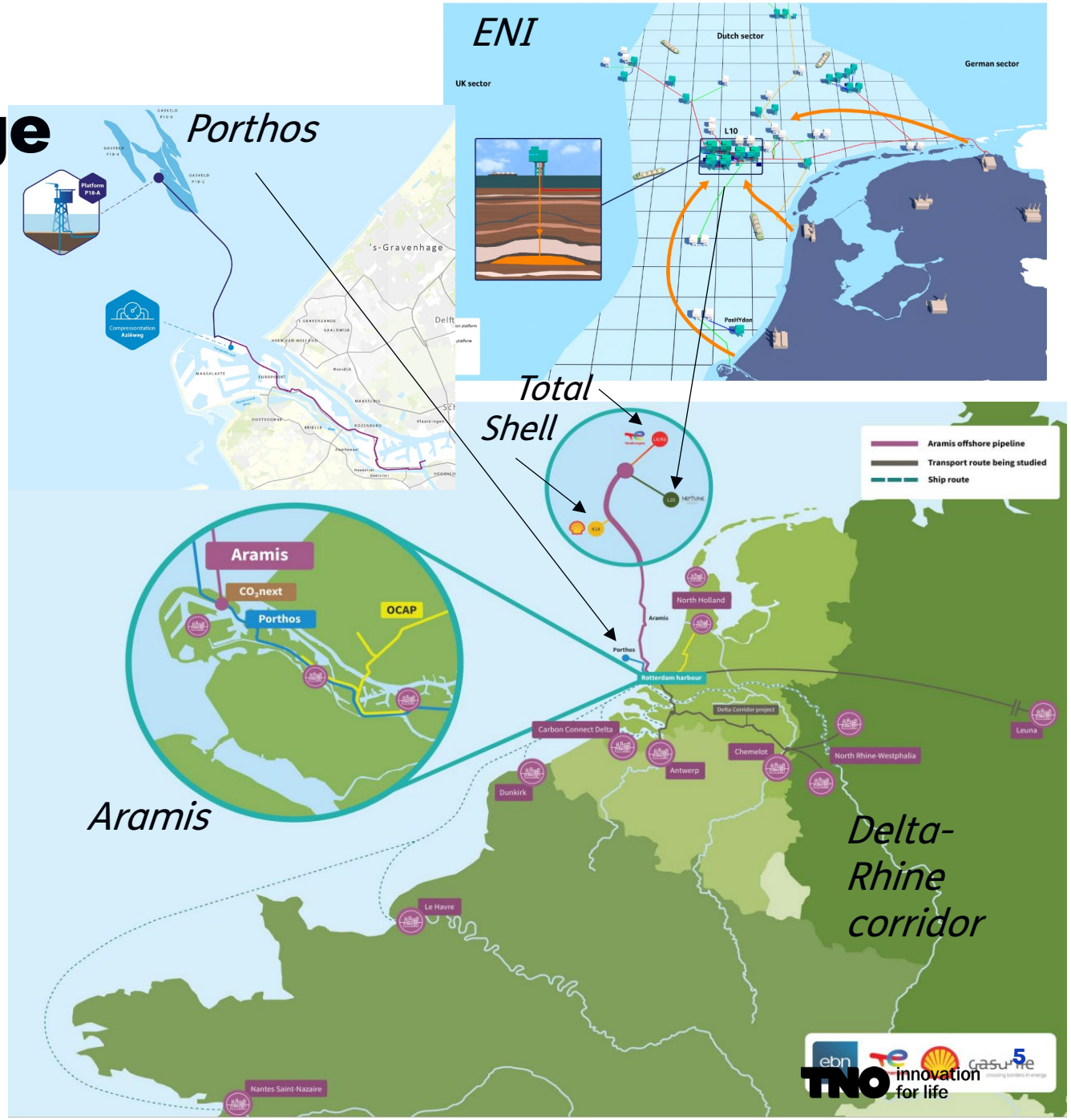
Emission Dutch industry: ~30 Mtpa



CO_2 transport and storage
DEVELOPMENTS IN NL

Currently ongoing

- **Porthos** project (in operation 2027)
  - P18 gas field cluster (~40 Mt, **2.5 Mtpa**)
- **Aramis** project (in operation 2030)
  - Trunkline Rotterdam – K,L blocks: **22 Mtpa**
- Shell: K14-FA (47 Mt, **2.5 Mtpa**)
- TotalEnergies: L4-A, K6-CA (40 Mt, **2.5 Mtpa**)
- CO_2Next: collection hub + ship terminal Rotterdam
- ENI: L10 fields (120-150 Mt, **2.5 - 5 Mtpa**)
- Yara Sluiskil (800 ktpa, storage Northern Lights, start Summer 2026)
- Delta-Rhine Corridor; connection to Antwerp, links with France



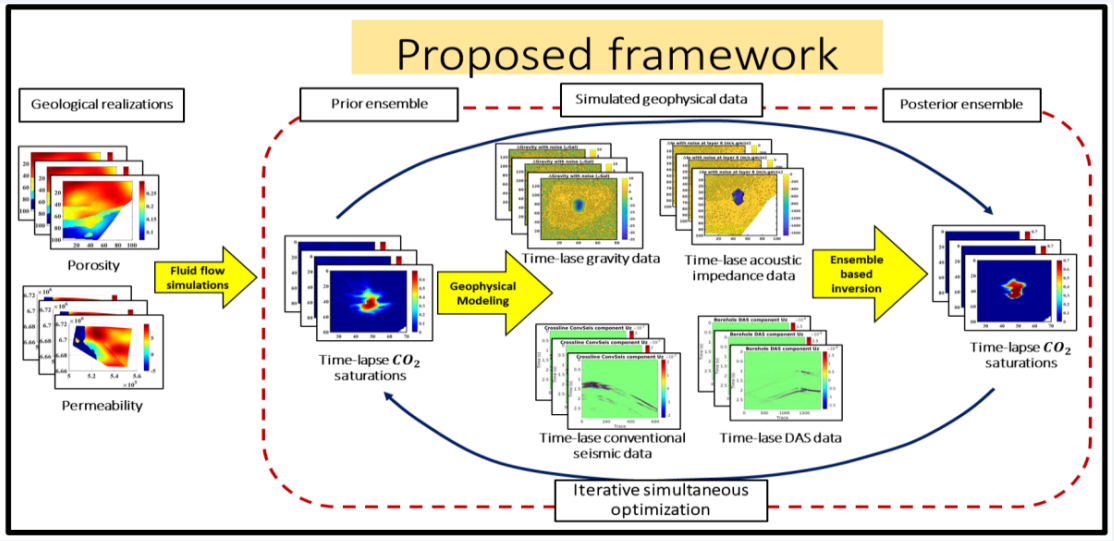
Link between R&D at TNO and EU-wide R&D targets

CO_2 transport and storage R&D @ TNO

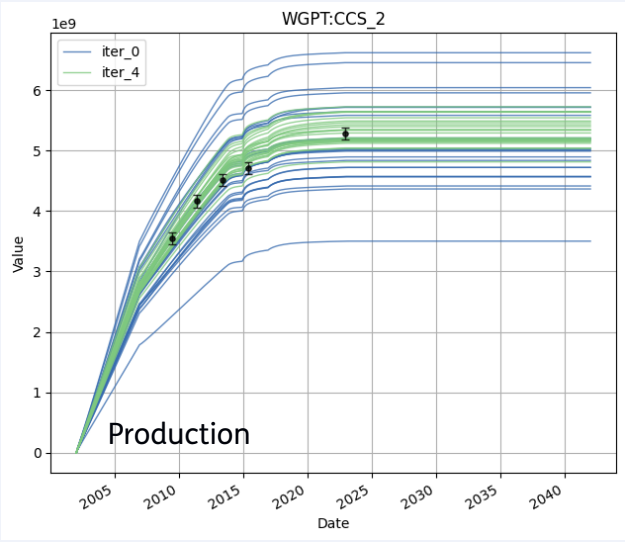
	Highlights of transport and storage topics currently covered in R&D projects at TNO	**Comment**	**Relevance (NL or EU R&D goals)**
S	**Monitoring, conformance assessment** (Ramonco)	Include geological uncertainty; define measures of conformance; assess the value of monitoring techniques and monitoring systems	**MMV reporting under the EU CCS Directive**
S	**Aquifer storage** – providing the basis for aquifer storage NL offshore (TKI DCSAS)	New regulations are needed in NL to allow pressure increase in aquifers	Support **new policy for aquifer storage** in NL
S	**Well integrity, leakage along wells** (JIP Eloquence)	Physics-based method to estimate migration along wells; norm-based permits	Address risk of **legacy wells**
S	**Well integrity** (WISCOS)	Portfolio screening of legacy wells	Address risk of **legacy wells**
S	**CO_2 quality** (SPECS)	Impact of impurities on storage system	Guidance for **CO_2 quality specifications**
S	**Storage site screening and development** (CO2SITE)	Create atlas of *investable* CO_2 storage sites in EU	**Storage options and capacity** Speed up development of CCS in Europe
S	**Porthos** storage project (CLARITY & POSEIMON)	Lessons learned, induced seismicity	**Best practices**, **reduce cost** of CCS **Monitoring system design**
T	**TNO lab** (RCSG)	Test CCS facilities in operational conditions	**Reduce cost** of CCS and ensure operational and asset integrity
T	**CO_2 quality** (IMPACT-CO2EU)	Impact impurities on transport system	Guidance for **CO_2 quality specifications**
T	**CO_2 flow loop** (ENCASE, CO_2Time)	Measuring and modelling of CO_2 flow in valves, chokes, etc	**Reduce cost** of CCS and operational and asset integrity
T	**Transport network simulation** (ACTION)	Assessing transport & storage network performance	Transport network design and operation **Reduce cost**

CETP Ramonco

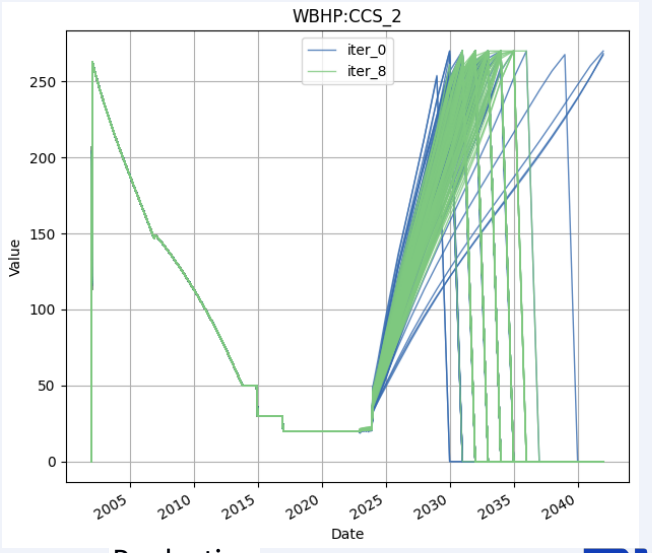
- **Conformance monitoring & assessment**
  - Ensemble-based history matching (including **geological uncertainty**!)
  - **Quantitative** conformance assessment
  - Monitoring system design
- **Joint inversion seismic and gravity data**
  - 3D images of CO_2 saturation in subsurface



2D workflow (from predecessor DIGIMON)



Production curves from gas field (above) and BHP (below) from ensemble members
BHP shows production and injection; spread of curves represents impact of geological uncertainty: uncertain duration of injection in each of the wells.
This impacts conformance assessment.
Blue: a priori production (top) and bhp curves
Green: HM with production data (black symbols)



CO_2 storage in aquifers: exploration

A **Aquifer**

Mapping 9 input parameters

B Computing 24 intermediate maps and calculating 4 basic maps

C **Theoretical CO2 Storage Capacity**

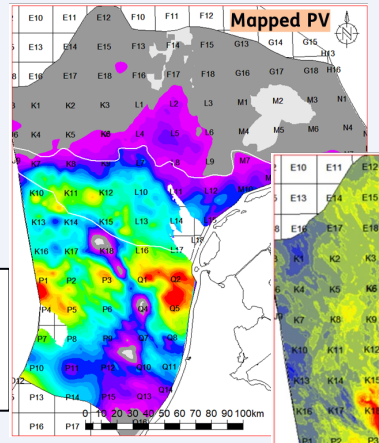
Multiplying 4 basic maps

and calculating capacity range

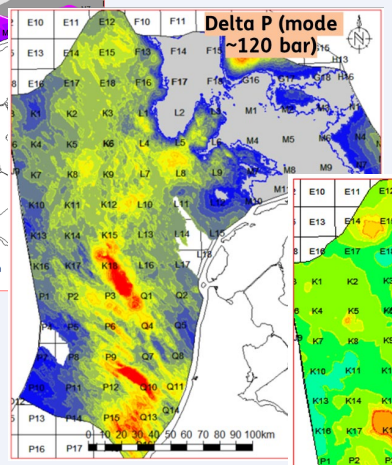
Theoretical CO_2 Storage Capacity

= **PV** x **delta P** x **Ct** x **Rho** *CO_2*

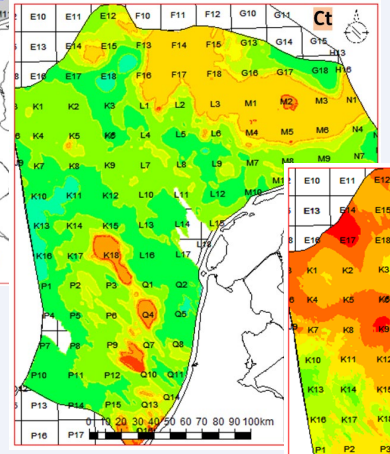
Pore Volume



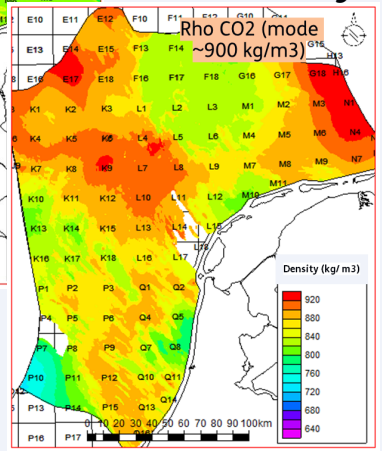
Delta P



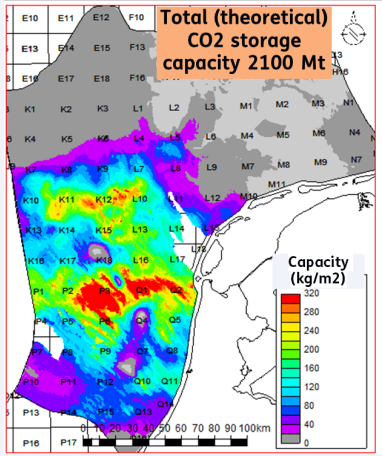
Total Compressibility



CO2 density



Theoretical CO2 storage capacity

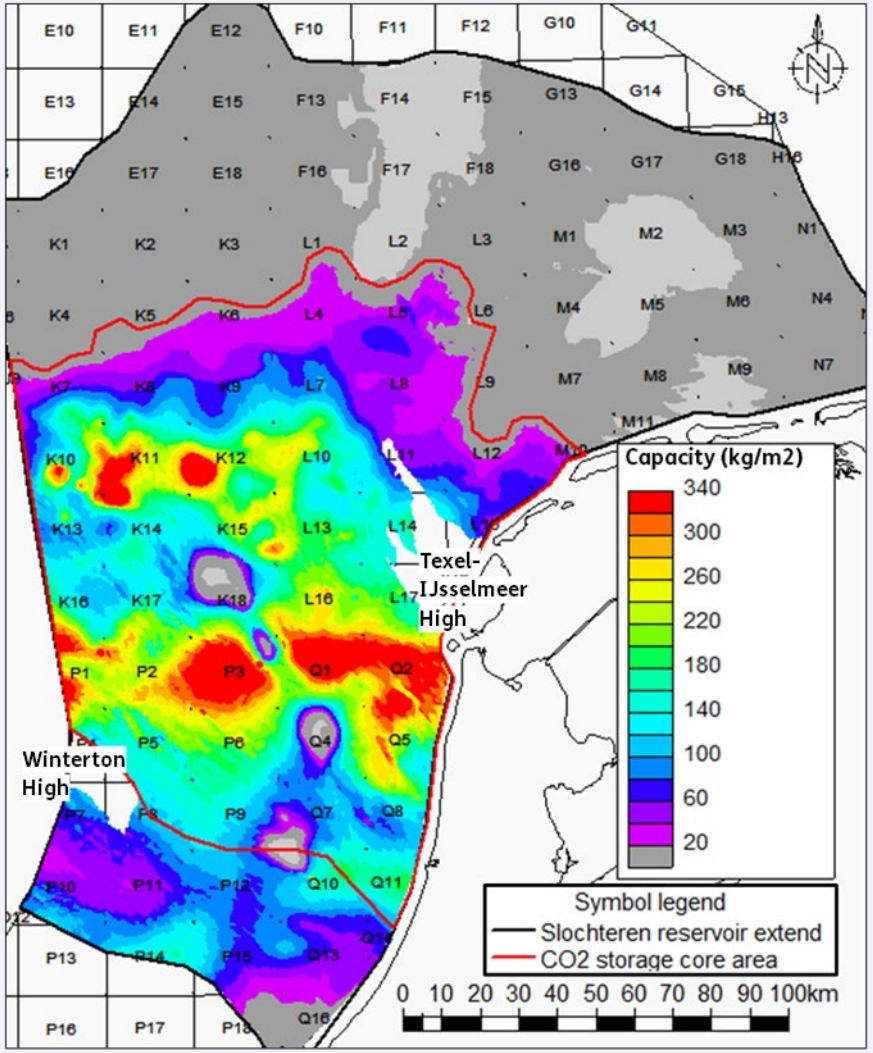


Rotliegend aquifer, NL offshore

[SCADSA study, TNO, 2025]

TKI CO_2 storage in aquifers

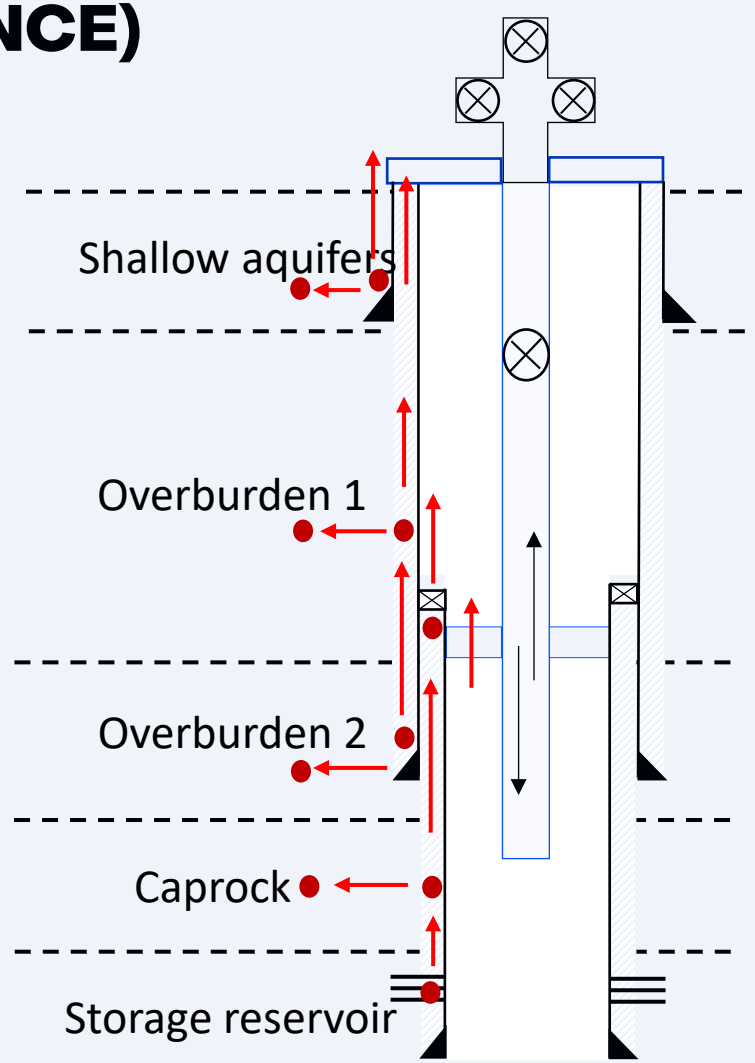
- Objective:
  - For relevant aquifer storage plays in Dutch offshore:
    - **explore the relation between pressure limit, storage capacity, and risk of loss of containment**
- Topic(s):
  - developing compartmentalised (i.e., relatively small) aquifer structures
  - using depleted fields with water leg
  - defining guidelines for maximum pressure definition
  - loss-of-containment-risk *vs* storage capacity *vs* maximum pressure
- Product / result
  - **Material for policy to enable aquifer storage on Dutch continental shelf**
- Partners: operators in Dutch offshore
  ENI, TotalEnergies, Shell, Petrogas, One-Dyas, EBN
- Timeline: start Q1 2025, duration 2 years



SCADSA study, TNO, 2025

Development of a tool for quantitative leakage assessment of legacy wells for abandonment and reuse (ELOQUENCE)

- Holistic leakage assessment tool that considers the entire well path and aims to predict the most likely leakage pathway as well as the leakage rate.
- The tool provides as assessment of the expected quality of the cement sheath (microannuli size) based on operational and in-situ conditions
- Such a tool facilitates quantitative leakage assessment of legacy wells for abandonment and reuse purposes
- The tool will incorporate results from lab experiments and will be verified by field cases (based in Norway, Netherlands or other regions of interest)
- Results from this tool form basis for norms (e.g., maximum allowed leak rates) for CO_2 storage permits



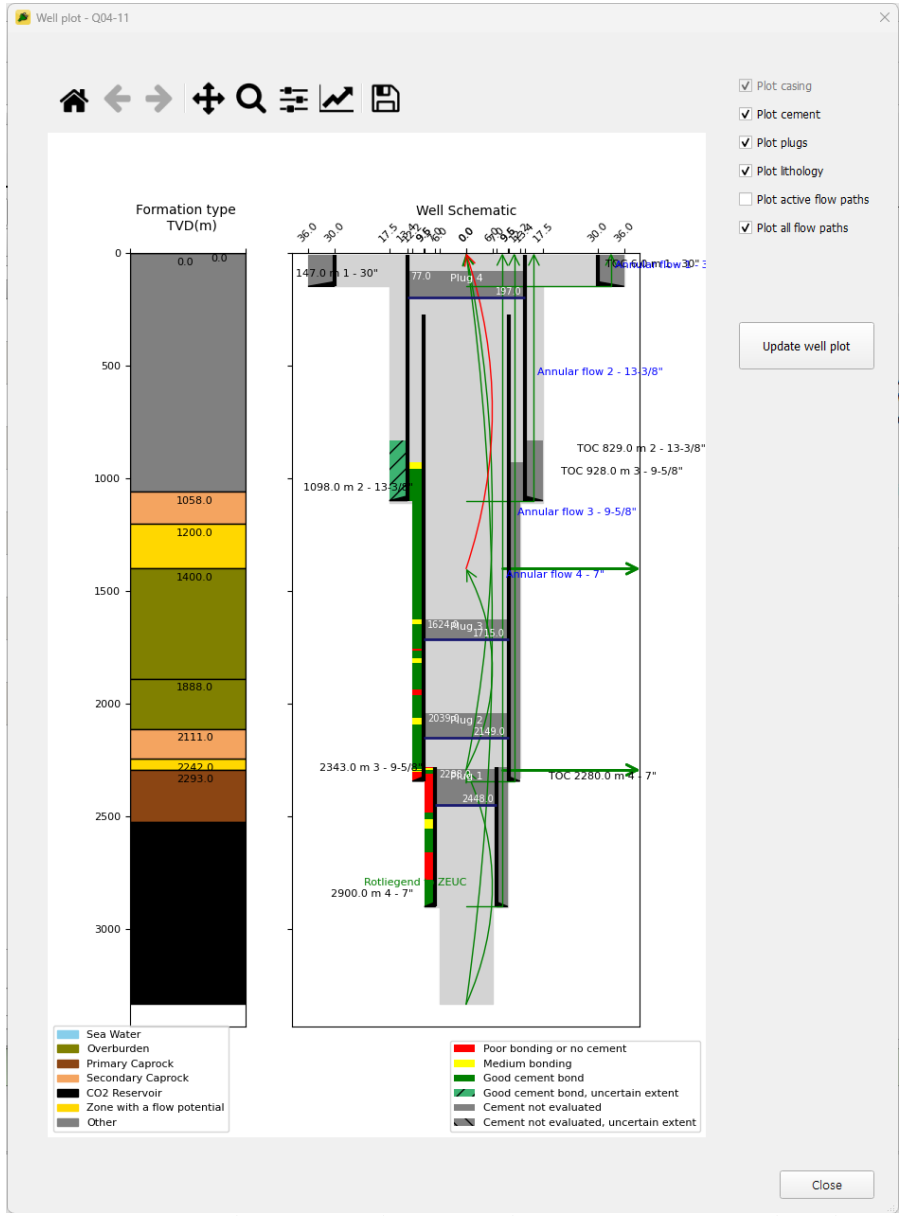
WELL INTEGRITY SCREENING

WISCoS tool - Well Integrity Storage Complex Screening

- Wiscos tool is a one-of-its kind well integrity screening tool that enables standardized risk assessment of all wells in the storage complex
  - **Support CCS Storage License & Permit Application process**
  - **Aid decision making to focus on critical wells**
  - **Reduce manhours and fast risk identification**
  - **Standardized approach in quickly screening large number of wells**

- Methodology and the tool developed as JIP between TNO, SINTEF and North Sea operators active in CCS
  - North Sea regulators indirectly involved

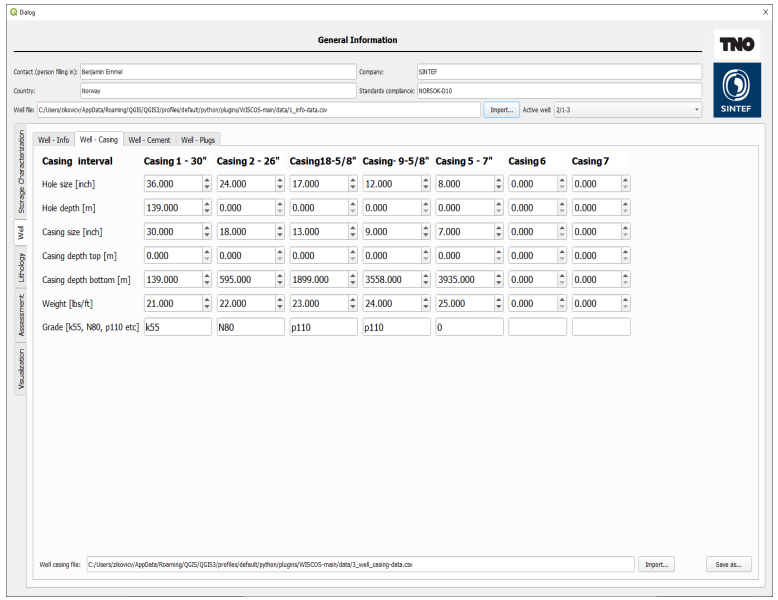
SINTEF TNO innovation for life TotalEnergies eni Shell OMV Harbour Energy



Outcome of Wiscos tool is a detailed well schematic with potential leak pathways based on integrity issues

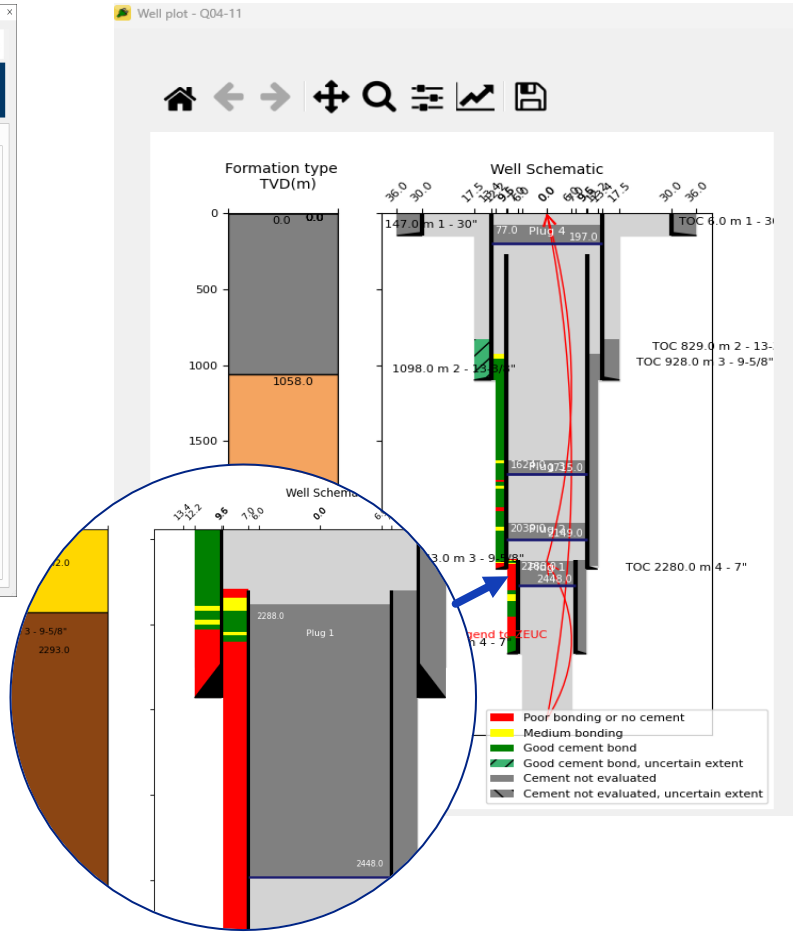
WISCOS WORKFLOW

Centralized data system



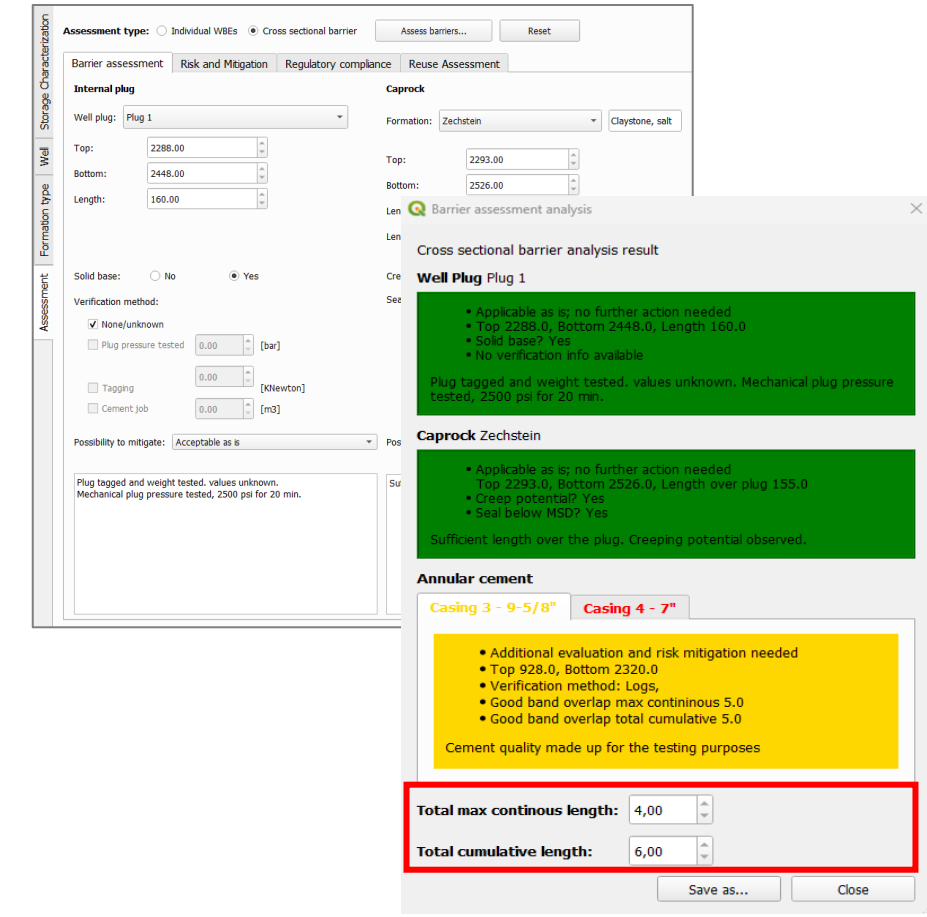
- Wells and storage data following standardized well reports

Generative well schematics



- At scale well schematics generated
- Visualisation of cement quality and availability of cross-section-barrier

Integrity screening & Risk assessment



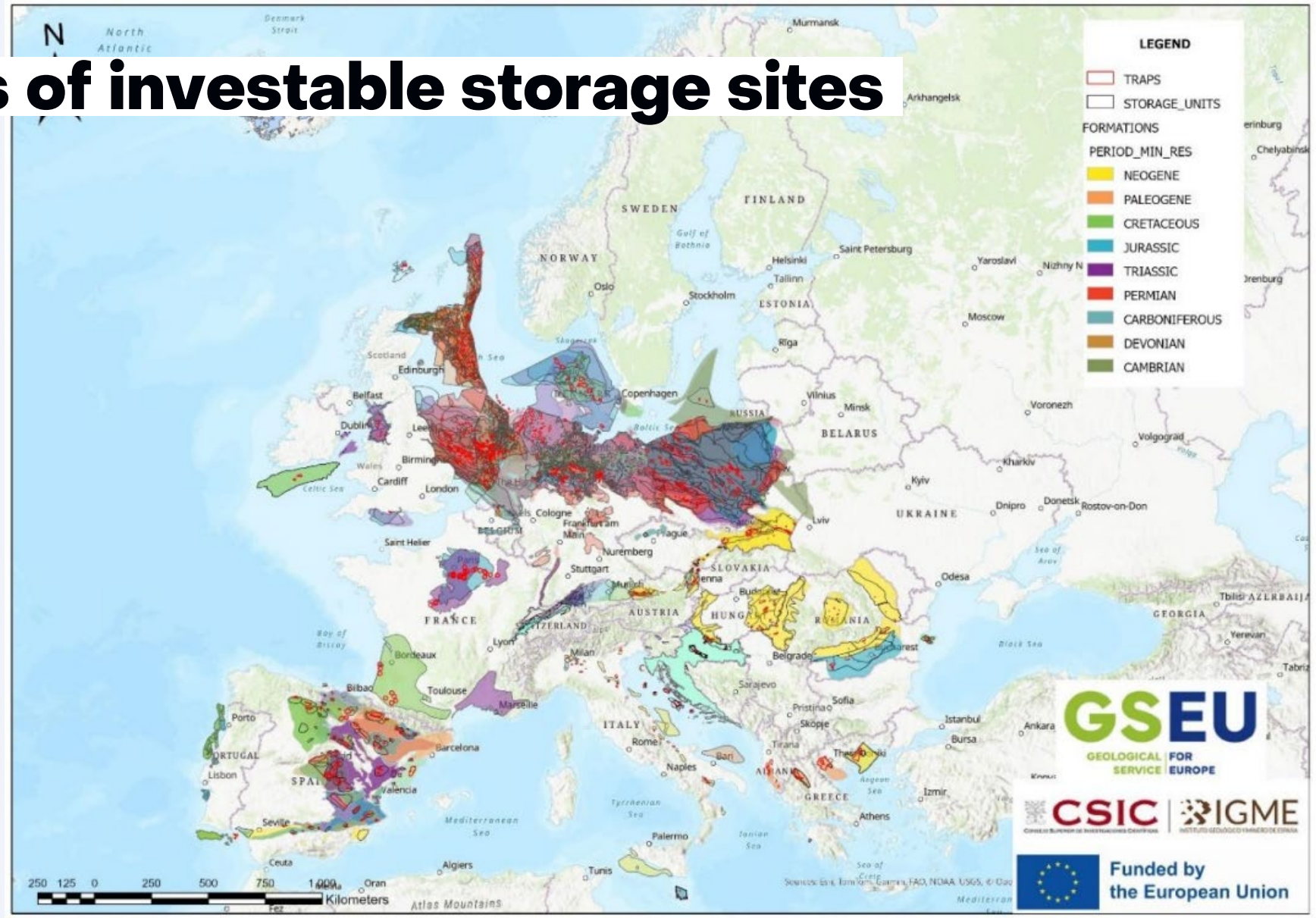
- Integrity screening per barrier element (caprock, plug, annular cement)
- Estimation of cross-sectional-barrier
- Standards compliance (NOGEPA 45, NORSOK D-010)

CO2SITE: atlas of investable storage sites

- EU funded project, TNO is coordinator
- June 2026 – June 2029
- Goal: storage atlas with *many* layers of information to support storage project developers in selecting the site(s) that best fit their requirements
  - Information includes economic drivers, proximity to CO_2 transport systems, legal and regulatory situation in the country of interest, etc., etc.
- Use best available starting point: GSEU CO_2 storage atlas

https://www.geologicalservice.eu/

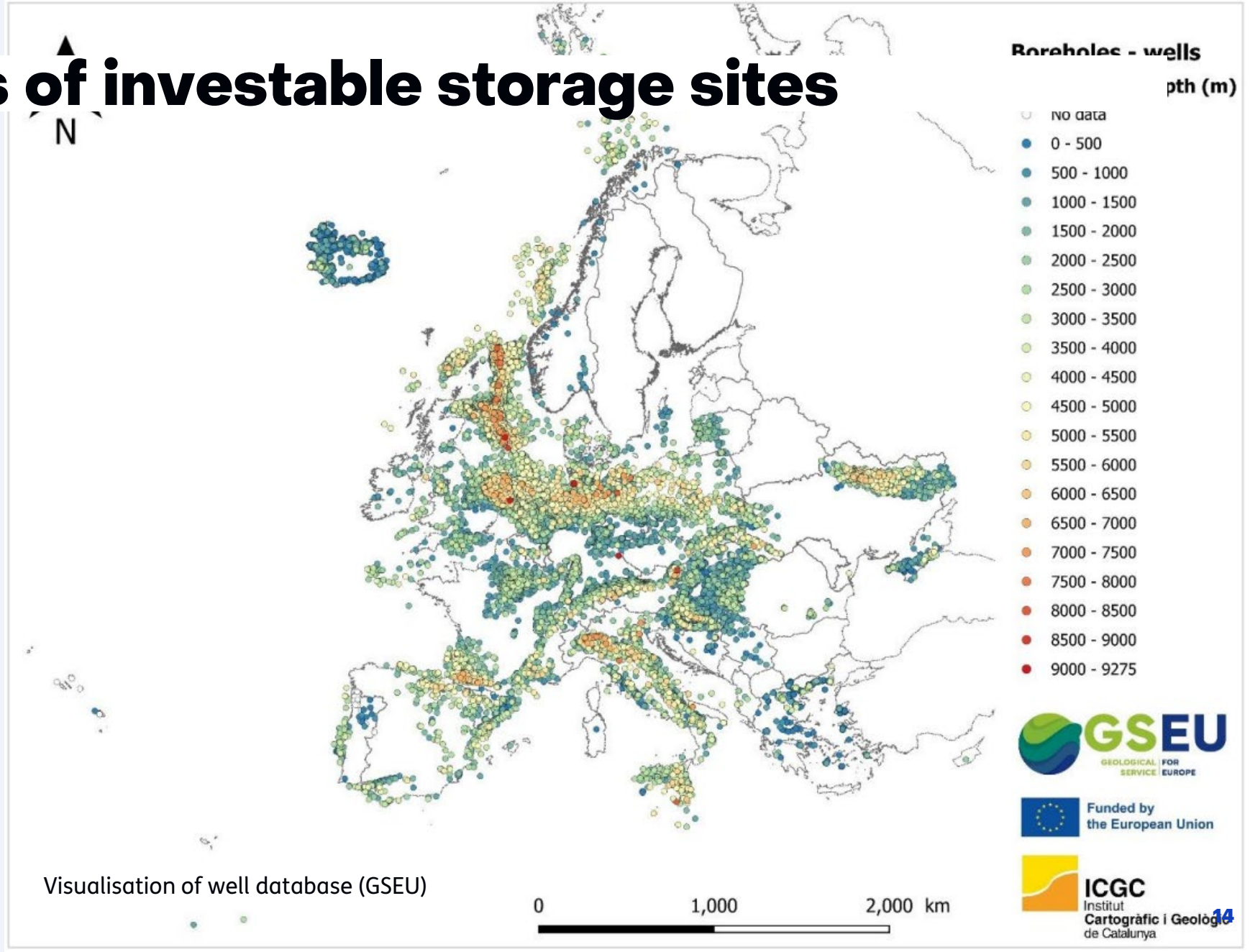
https://eurogeosurveys.org/new-op-ed-co2-storage/



Example of the formations, storage units and traps visualization in the Pan-European Atlas of CO_2 storage

CO2SITE: atlas of investable storage sites

- Example in figure: wells database
- Relevance:
  - Presence of legacy wells
  - Data about well layout
  - Information about abandonment date and method
  - Well logs and their availability
- Such data informs the risk state, information availability, information owners, etc.



Visualisation of well database (GSEU)

CO_2 storage in The Netherlands
Best practices, induces seismicity monitoring

CLARITY - Porthos Lessons Learned

- Porthos CO_2 storage project – start date in 2027
- Goal project: **derive lessons learned from transport and storage for benefit of other storage projects in The Netherlands and abroad**
- Project to cover 5 years to include transition from gas phase to liquid phase
- Project start 2026


Porthos pipeline, 2024


Porthos compressor, 2024

POSEIMON I and II - Induced seismicity (I), active seismic methods (II)

- Porthos project: no detailed monitoring of induced seismicity
- Goal projects: (1) install microseismic network, monitor during injection of CO_2, evaluate the value of microseismic monitoring for Dutch storage projectsl; (2) deploy and test methods of active seismic monitoring
- Project to cover 5 years to include transition from gas phase to liquid phase
- Project start Q2 2026

TNO WELL TECHNOLOGIES LAB FACILITIES

Rijswijk Centre for Sustainable Geo-energy (RCSG)

Drill rig + wells (~600 m)

Lab facilities

Ministry of Economic Affairs and Climate Policy

ebn

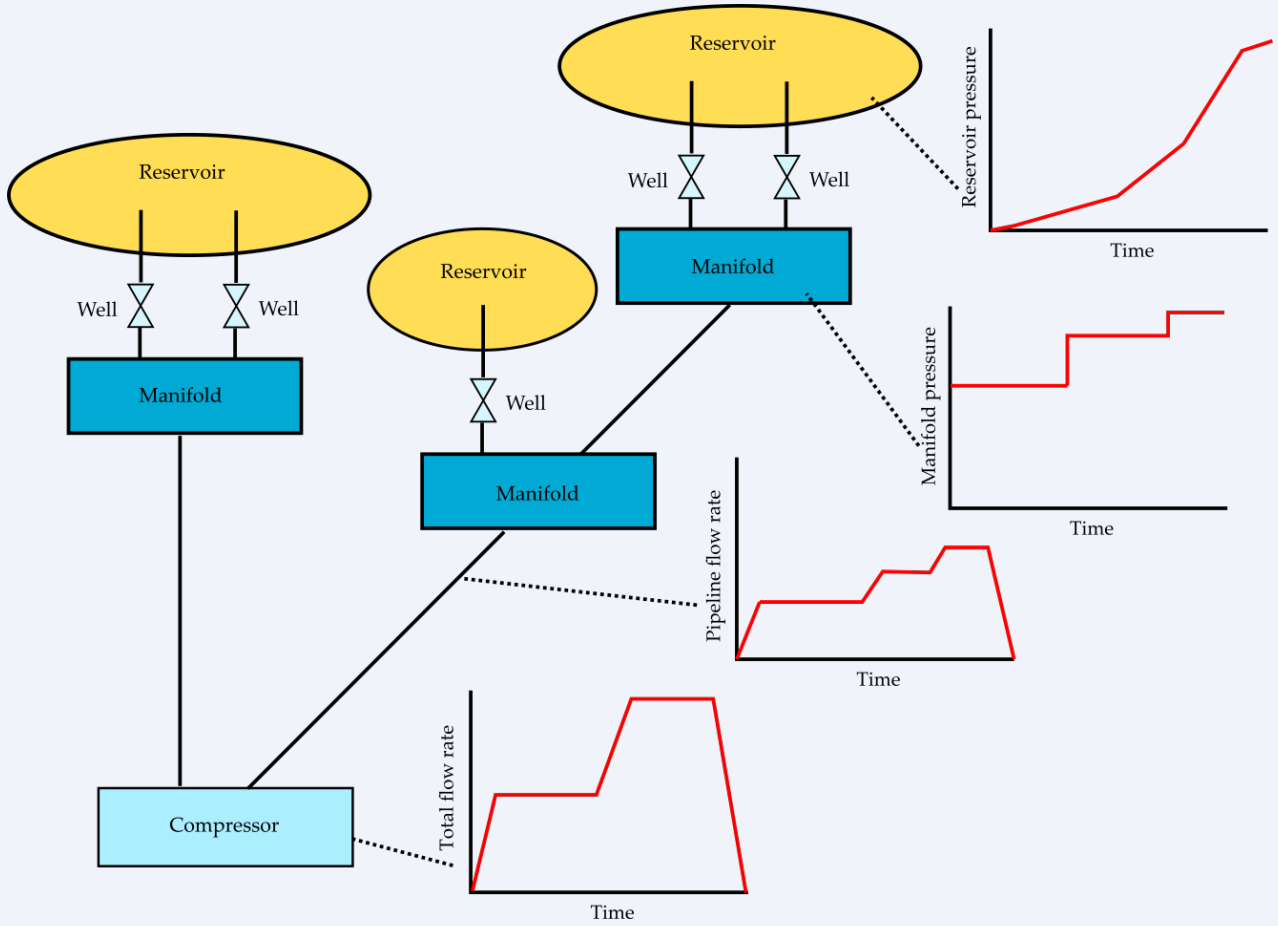
provincie ZUID HOLLAND

Rijswijk

ACT ACTION

- **CO_2 transport and storage network evolution**
- 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

- Result
  - Steady-state model to study flow in complex networks, with proxy models for wells and reservoirs
  - Step-wise steady-state, accommodating flow and boundary conditions varying over time
  - Current work: optimise flow distribution over network



The ACTION model can represent reservoirs with different properties, slowly filling up over time, to study the optimum management of network conditions (i.e., pressure and CO_2 distribution over injection sites)

CO_2 quality – high-priority topic in EU

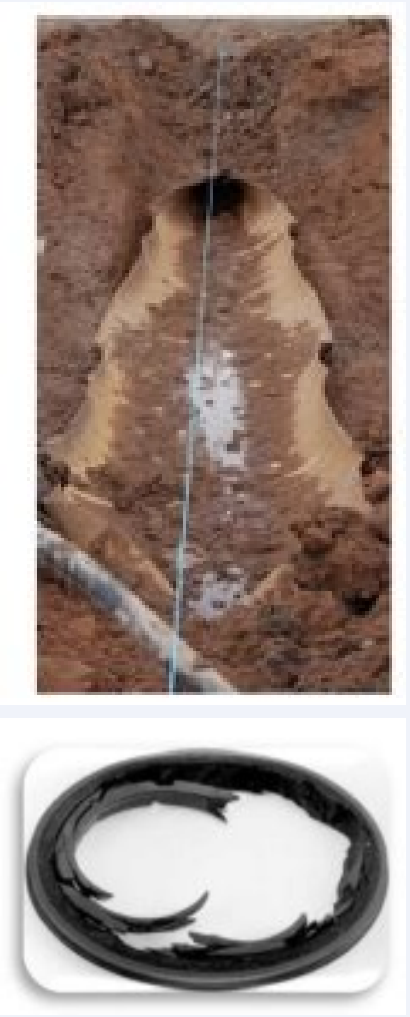
Two new projects starting at TNO on topic of CO_2 quality

SPECS: CO_2 quality & storage

- Goal project:
- EU funded project, coordinator:IFPEN (France)
- Topics: impact impurities on storage fm, on well materials, on well performance, contribute to standards
- Project start June 2026

IMPACT-CO2EU: CO_2 quality & transport

- Goal project:
- EU funded project, coordinator: IFE (Norway)
- Topics: impurity chemistry, corrosion, thermo-physical properties of mixtures, impact on pipeline flow and ship offloading, contribute to standards
- Project start June 2026



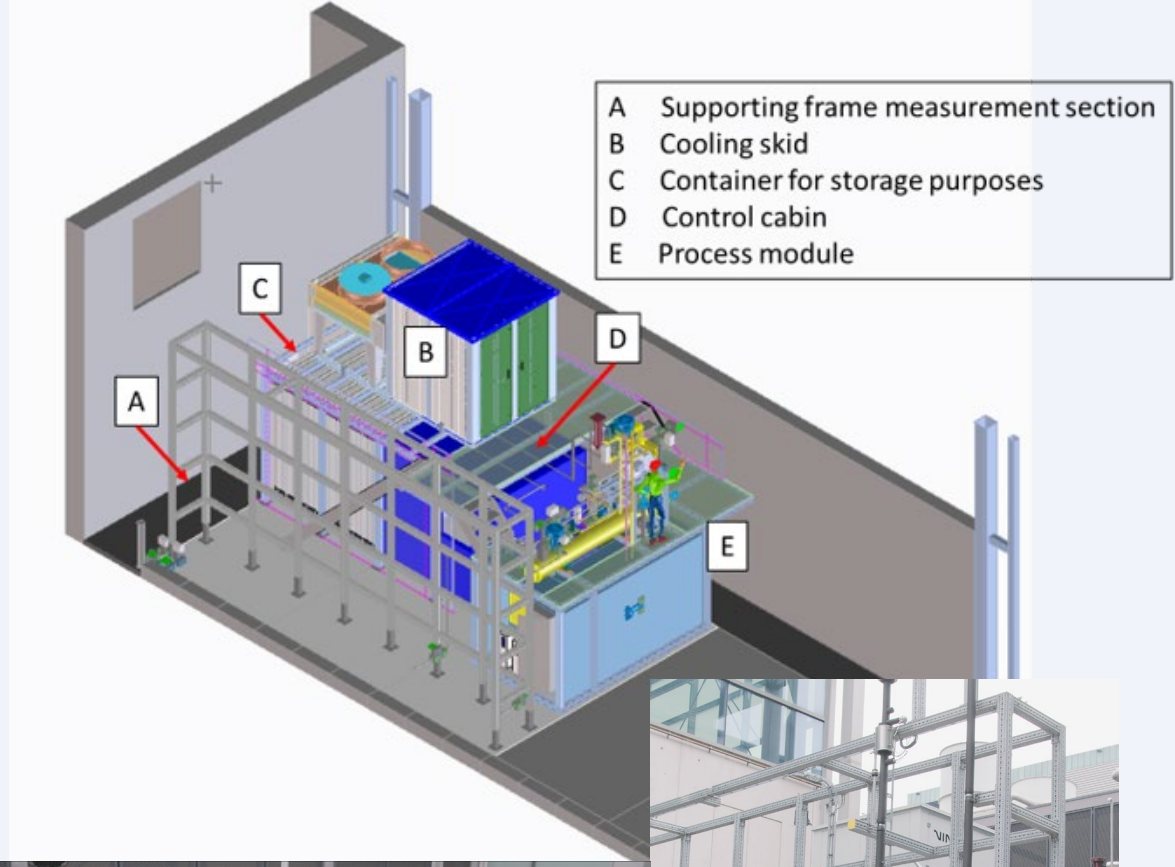
CO_2 interaction with materials in the CCS chain (not from TNO projects)

CO_2 flow loop

- Projects: CO_2-TIME, ENCASE
- Flexible and modular facility to **investigate CO_2 behaviour for e.g. bends, valves, chokes, instruments, other vertical & horizontal appendages, porous media**
- CO_2 composition: pure CO_2 and CO_2 mixtures
- Accurate control and read-out of pressure, temperature and flow rate
- Flow lines ID of ½”-1”

- Key numbers

	Min	Max
Flow rate gas		20/5 m/s
Flow rate liquid		1-2 m/s
Pressure		100 bar
Pressure drop		75 bar
Temp	-50 °C	+ 40 °C



THANK YOU FOR
YOUR TIME

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