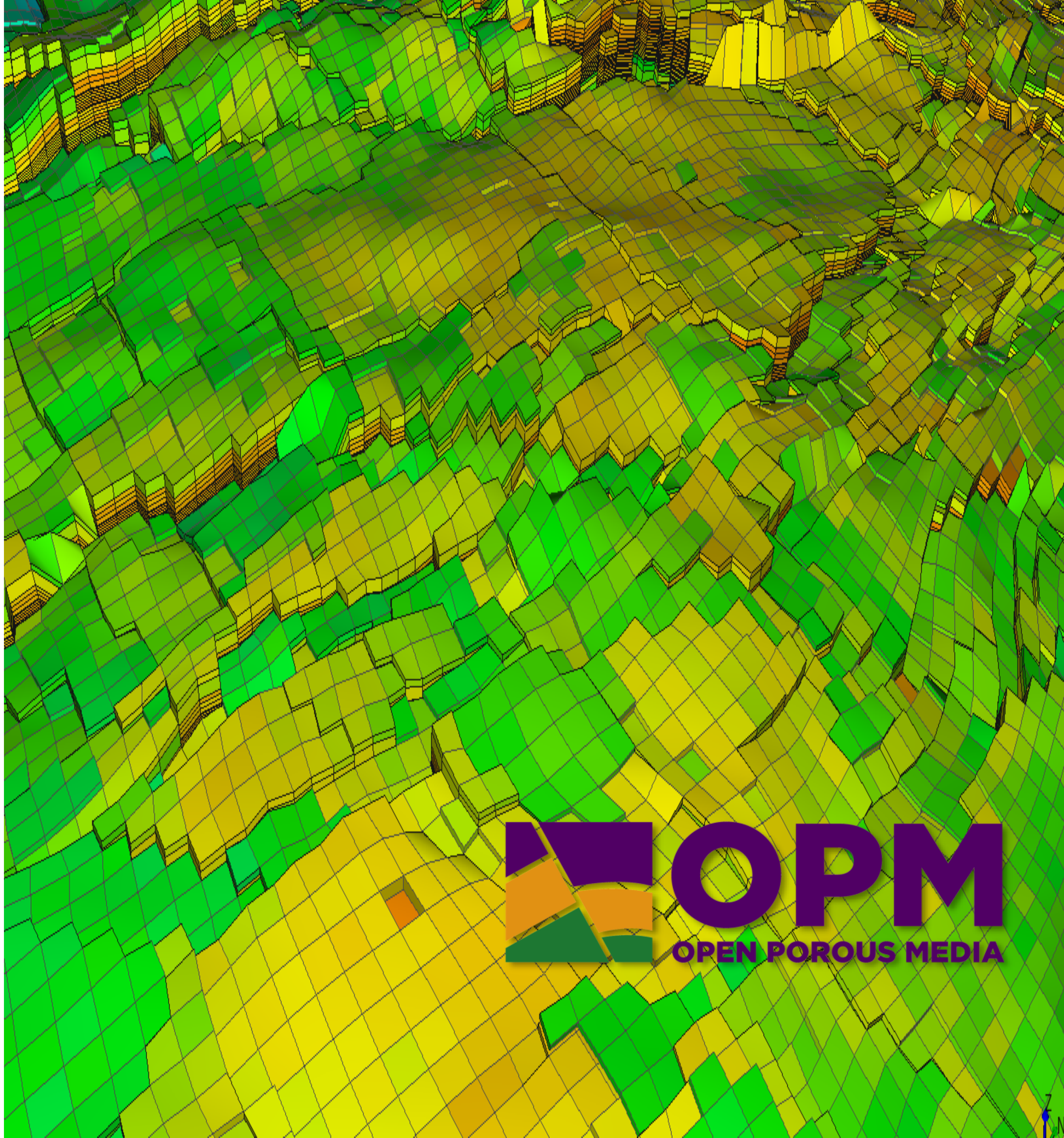
Examples of OPM-Flow usage at TNO

OPM Summit 2024

Negar Khoshnevis



April 9-10, 2024

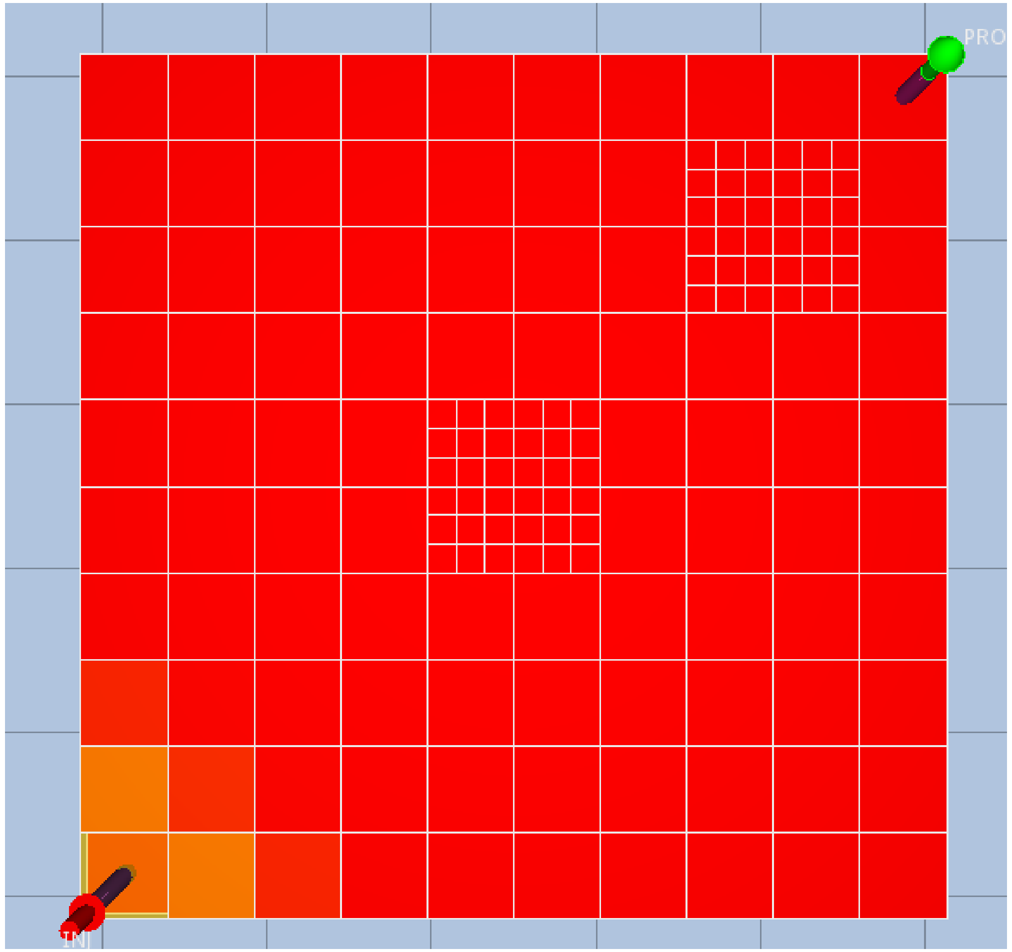
TNO innovation for life

Outline

- LGR test case
- Groningen case
- Applications at TNO
  - High-temperature seasonal heat storage (HT-ATES)
  - CO_2 storage in aquifers
  - Seismicity effect of depletion in aquifers
- Demand for new features at TNO
  - Thermal-phase change
  - H_2 storage and bio/geochemistry
  - Fractured reservoirs: dual-poro / dual-perm

LGR test case

LGR test case
SPE1




```
DX
300*1000 /
DY
300*1000 /
DZ
100*50 100*50 100*50 /


PERMX
100*500 100*50 100*200 /
PERMY
100*500 100*50 100*200 /
PERMZ
100*500 100*50 100*200 /


CARFIN
NAME    I1  I2  J1  J2  K1  K2  NX  NY  NZ
'LGR1'   5   6   5   6   1   3   6   6   9 /
ENDFIN

CARFIN
NAME    I1  I2  J1  J2  K1  K2  NX  NY  NZ
'LGR2'   8   9   8   9   1   3   6   6   9 /
ENDFIN
```

LGR test case

- **Validation of transmissibility values:**
  - Reporting values calculated by ref. simulator, comparing with values internally calculated in OPM by Antonella (incl. unit conversion)
  - Identifying need for correction factors (“reverse engineering”)
  - LGR-LGR transmissibilities:

		index	dx	dy	depth	permx	NTG	dz	DHS	DVS	DIPC	B	A	TranX(CPB	TRANX(ft3)-An	(CPB/D/PS	9,41738E-09
tranx	global	1,1,1	1000	1000	8350	500	0,333333	20	444444,4	277,8889	0,999375141	1,333333333	2222,222	1,87716	1,76873E-11		
	local	4,5,1	333,3333	333,3333	8333,33	500	0,333333	6,666667									

```
NO.      HOST CELL        LOCAL CELL       CONNECTED       TRANSMISSIBILITY     DIRECTION
                                          GLOBAL CELL       IN CPB/D/PS
        (I,   J,   K)    (I,   J,   K)    (I,   J,   K)

  1      5    5    1       1    1    1      4    5    1       1.87833328           X-
```

reference simulator

  - LGR-global transmissibilities:

		index	dx	dy	depth	permz	NTG	dz	A	B	TRANz(CPB/D/	TRAnZ(ft3)-Antonella
tranz	local	6,1,4	333,33	333,3333	8350	50	1	10	111109,3	0,10666	1174,012923	1,1062E-08
	local	6,1,3	333,33	333,33	8341,67	500	1	6,66				

```
(I,   J,   K)  I=   1        2        3        4        5        6

(*,   1,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
(*,   2,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
(*,   3,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
(*,   4,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
(*,   5,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
(*,   6,   3)    1174.0   1174.0   1174.0   1174.0   1174.0   1174.0
```

reference simulator

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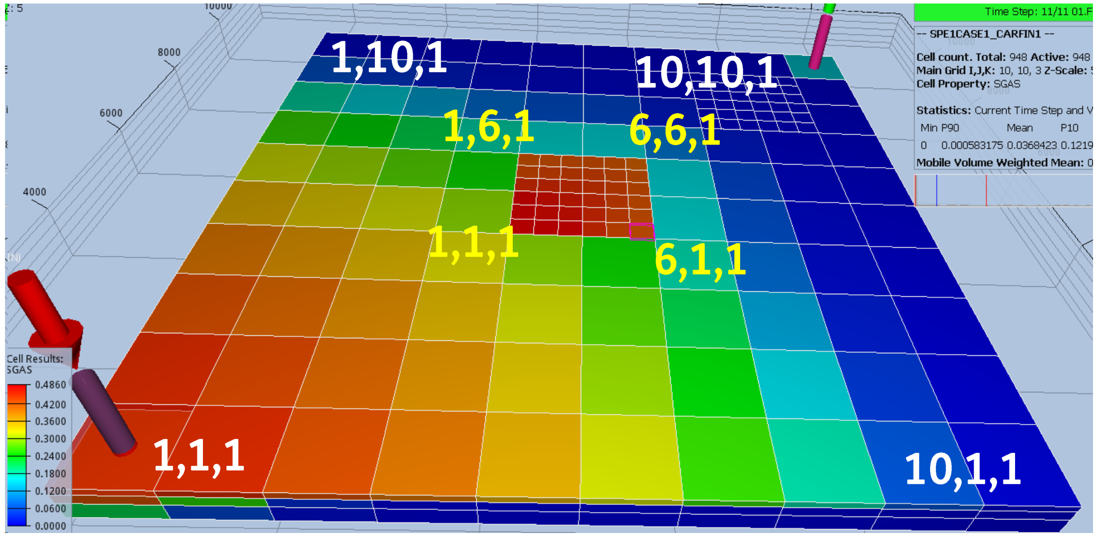
LGR test case

	Global Grid	Local Grid	Ref simulator (CPB/D/PS)	Ref simulator (m3)	OPM(m3)
TranX	4 5 1	1 1 1	1,87833328	5,0130E-13	2,0054E-13
TranX	7 5 1	6 1 1	1,87833328	5,0130E-13	5,0136E-13
TranX	5 7 1	1 6 1	1,87833328	5,0130E-13	5,0136E-13
TranX	6 4 1	6 1 1	1,87833328	5,0130E-13	2,0054E-13
TranX	4 5 2	1 1 4	0,28174999	7,5196E-14	3,0081E-14
TranX	7 5 2	6 1 4	0,28174999	7,5196E-14	7,5204E-14
TranX	7 6 3	6 6 9	1,87833328	5,0130E-13	5,0136E-13

	Local Grid	Local Grid	Ref simulator (CPB/D/PS)	Ref simulator (m3)	OPM(m3)
TranX	1 1 1	2 1 1	3,7567	1,0026E-12	1,0027E-12
TranZ	1 1 1	6 5 1	9391,7	2,5065E-09	2,5068E-09
TranZ	1 1 4	1 1 3	1174	3,1333E-10	3,1335E-10
TranZ	1 1 4	1 1 5	626,11	1,6707E-10	1,6712E-10
TranX	1 1 4	2 1 4	0,5635	1,5039E-13	1,5041E-13
TranZ	1 1 9	1 1 8	1502,7	4,0105E-10	4,0109E-10

- Comparison of transmissibilities
  - OPM-Flow vs. reference simulator
  - Local-local transmissibilities are in agreement
  - Mismatch in local-global X- and Y- transmissibilities (by same factor) → correction needed



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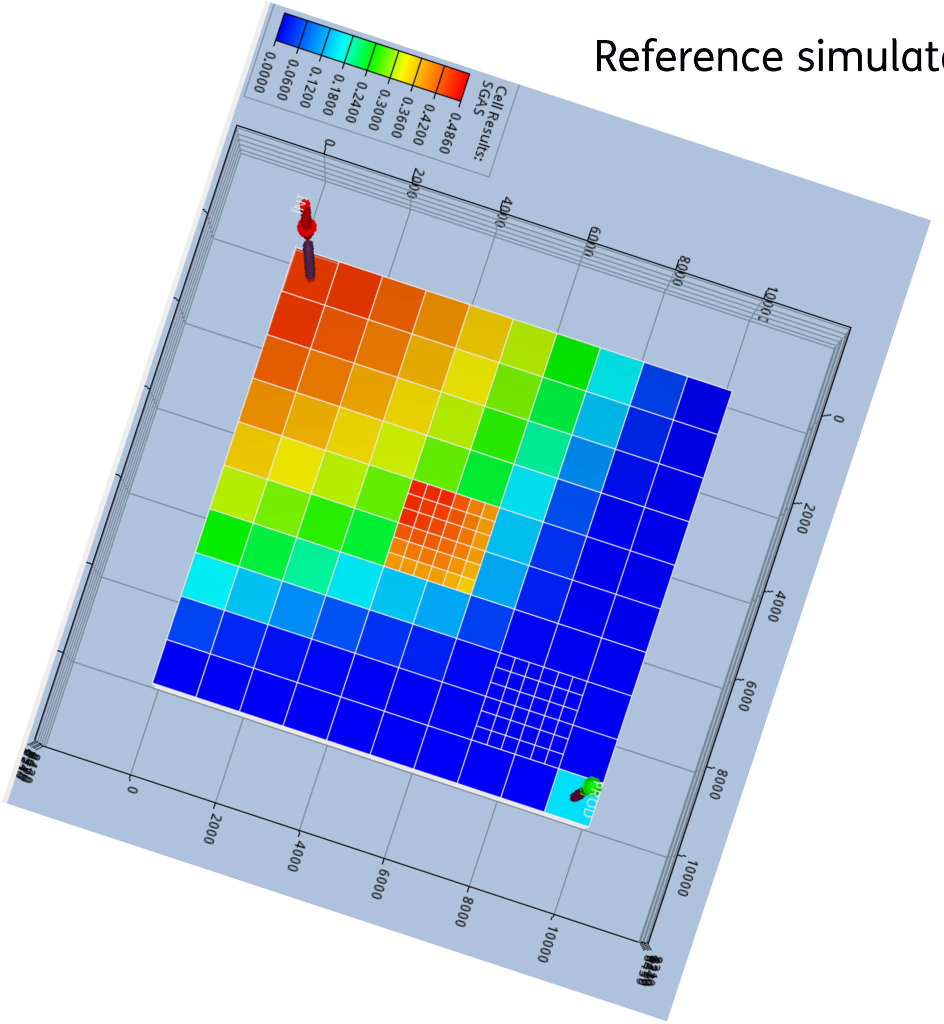
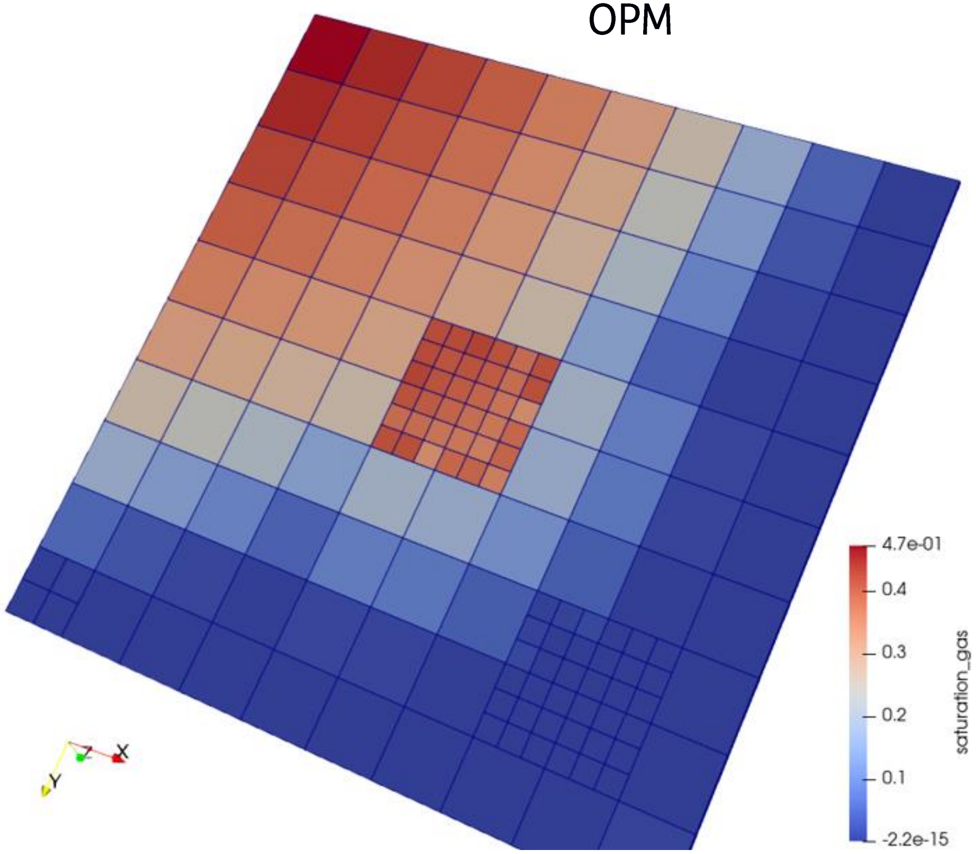
LGR test case

Comparison of gas saturation distribution:

Reference simulator

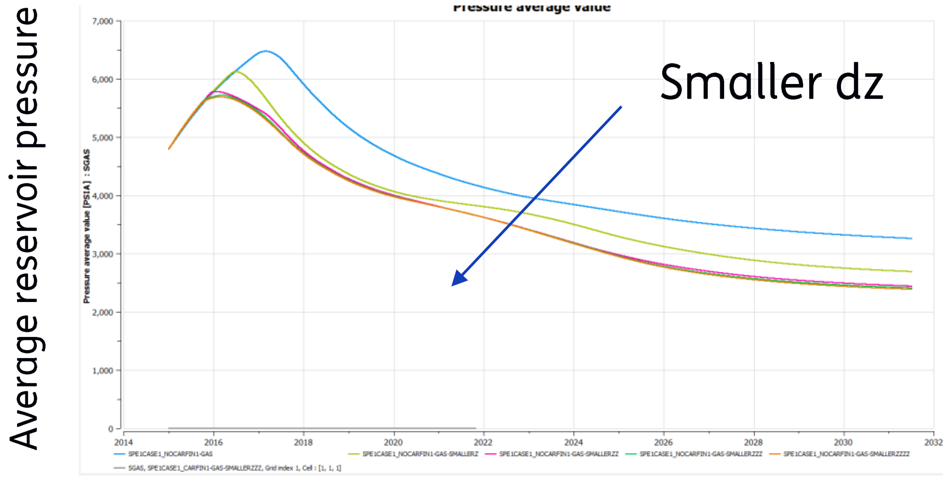


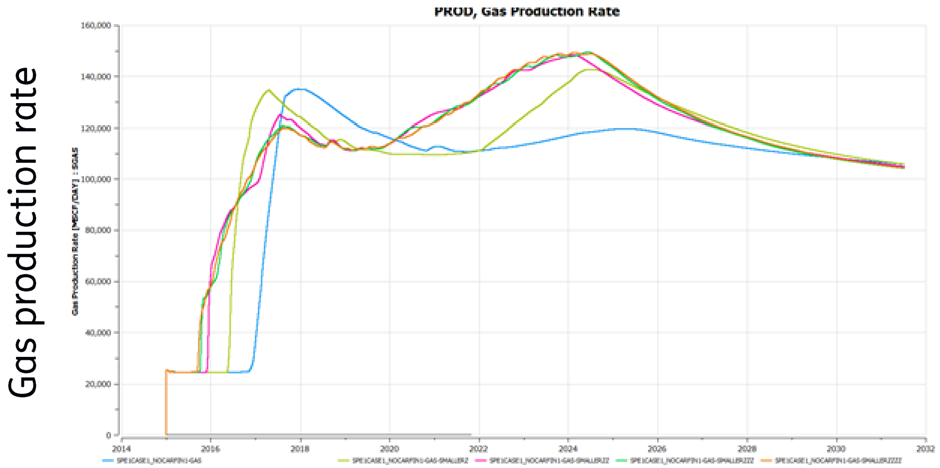
OPM

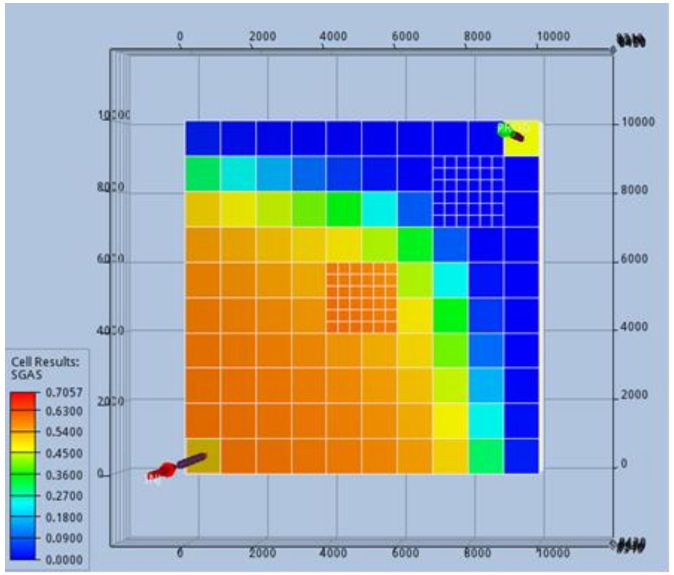


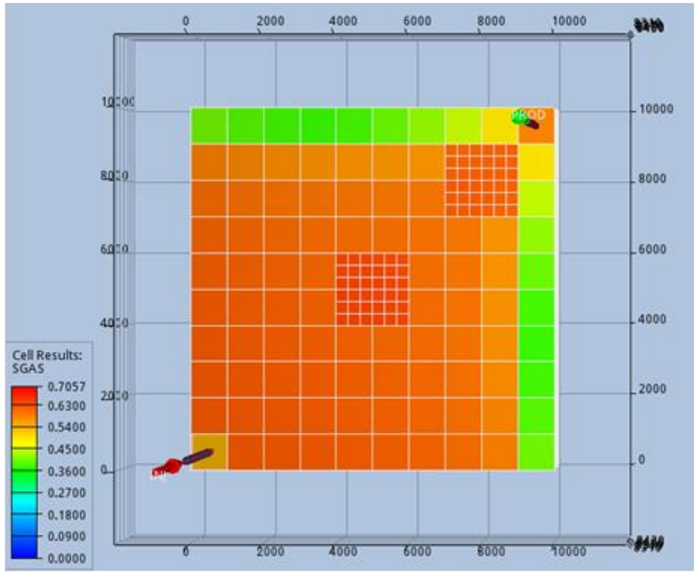
LGR test case

- **Adjusting test case:**
  - Original case shows numerical artifacts (mobility of inject gas varies significantly based on vertical resolution of grid)





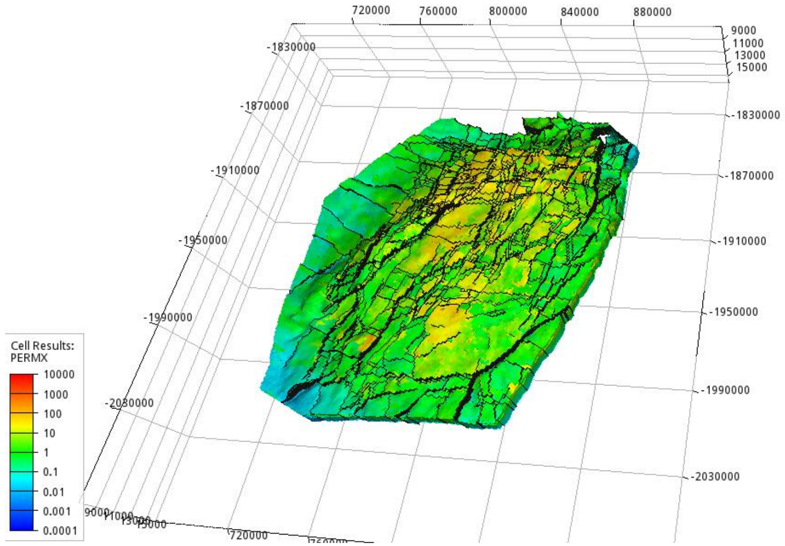


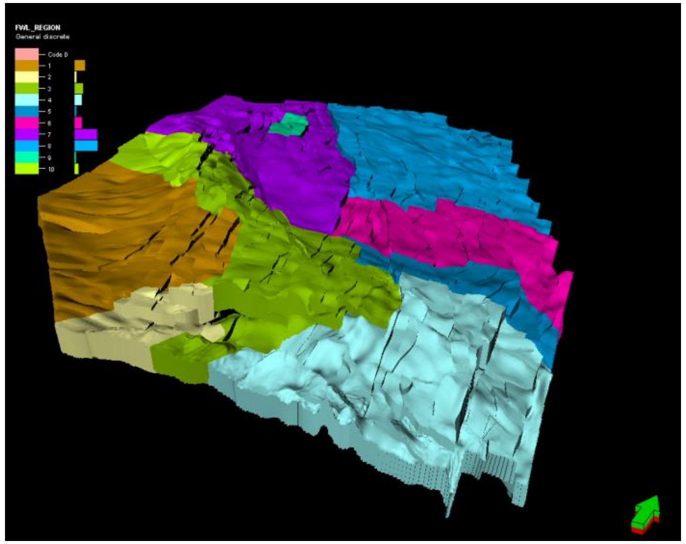


Groningen test case

Status large-scale test case

- **Approach:**
  - Build multi-million grid cell reservoir simulation model based on publicly available Groningen dataset (released by NAM / Shell)
- **Exporting static model:**
  - Two static models in Petrel: with 18 million and 38 million grid cells
  - Field extent: 40 × 50 km, gas column ~444 m
  - Average grid size: 100 × 100 × 5 m
  - 665 faults
  - 10 different GWC's
- **Building dynamic model (on-going):**
  - Add regions (EQLNUM, PVTNUM, and SATNUM)
  - Add 4 aquifers
  - Add PROPS
  - Add wells location, SCHEDULE and history of production
  - 300+ wells (gas and water producers)

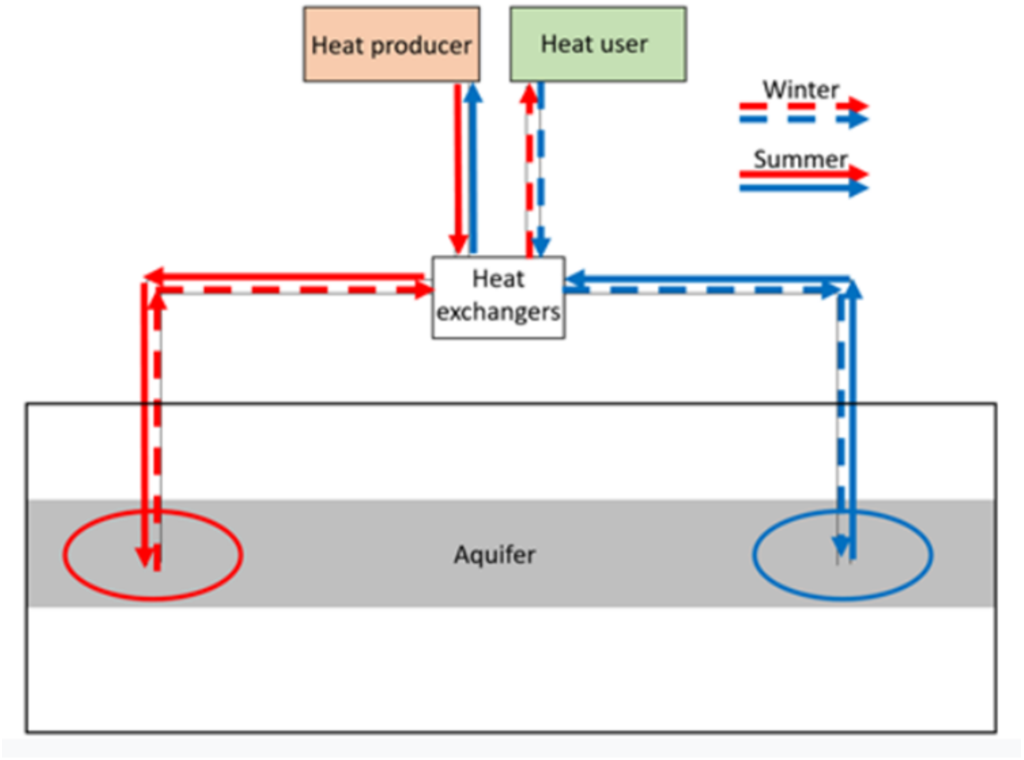


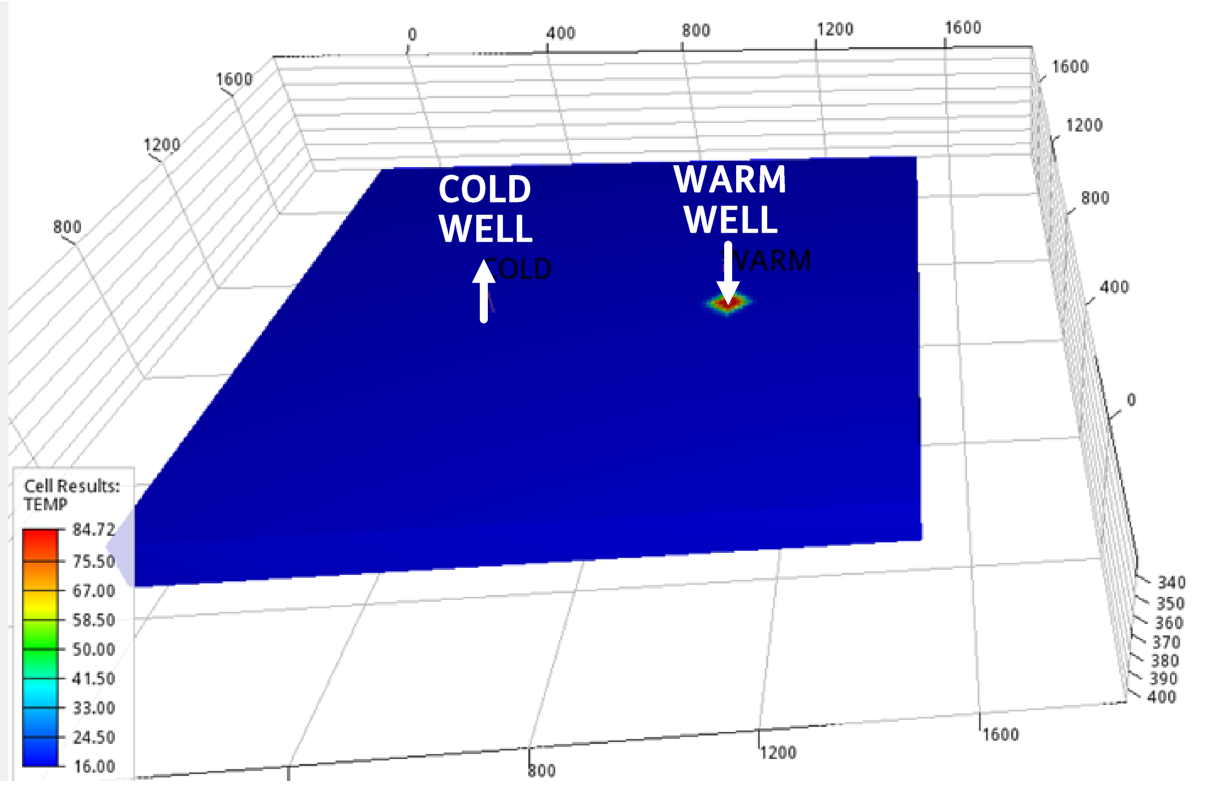


Applications of OPM-Flow at TNO

Applications at TNO

High-temperature aquifer thermal energy storage (HT-ATES)

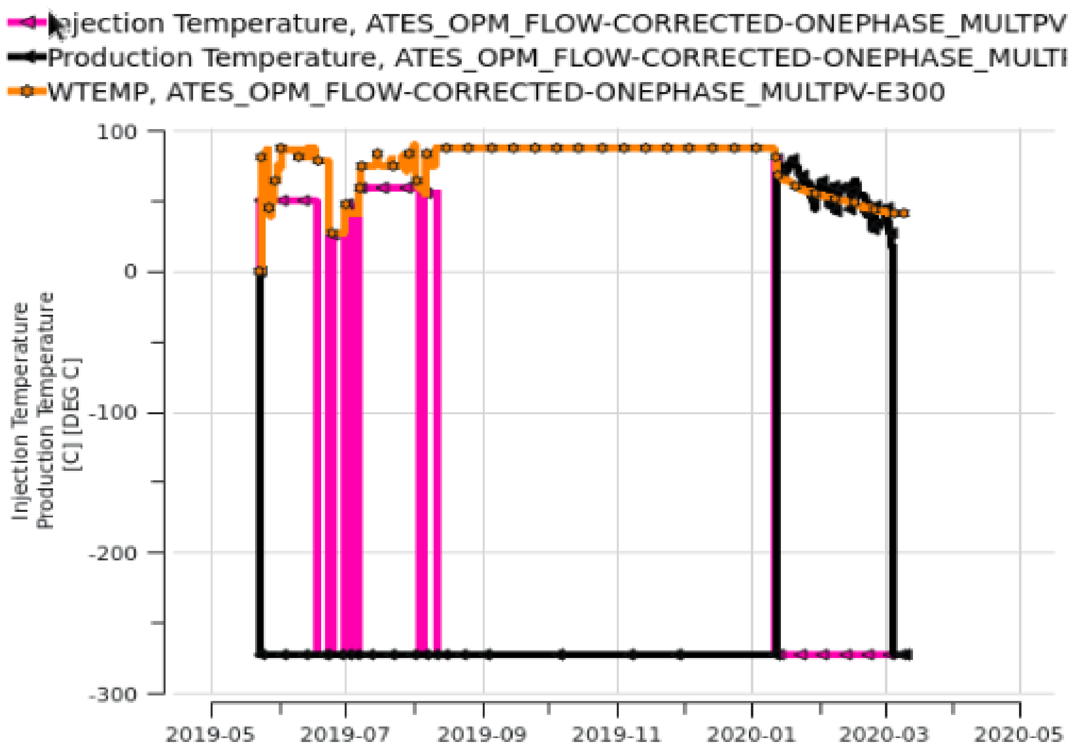




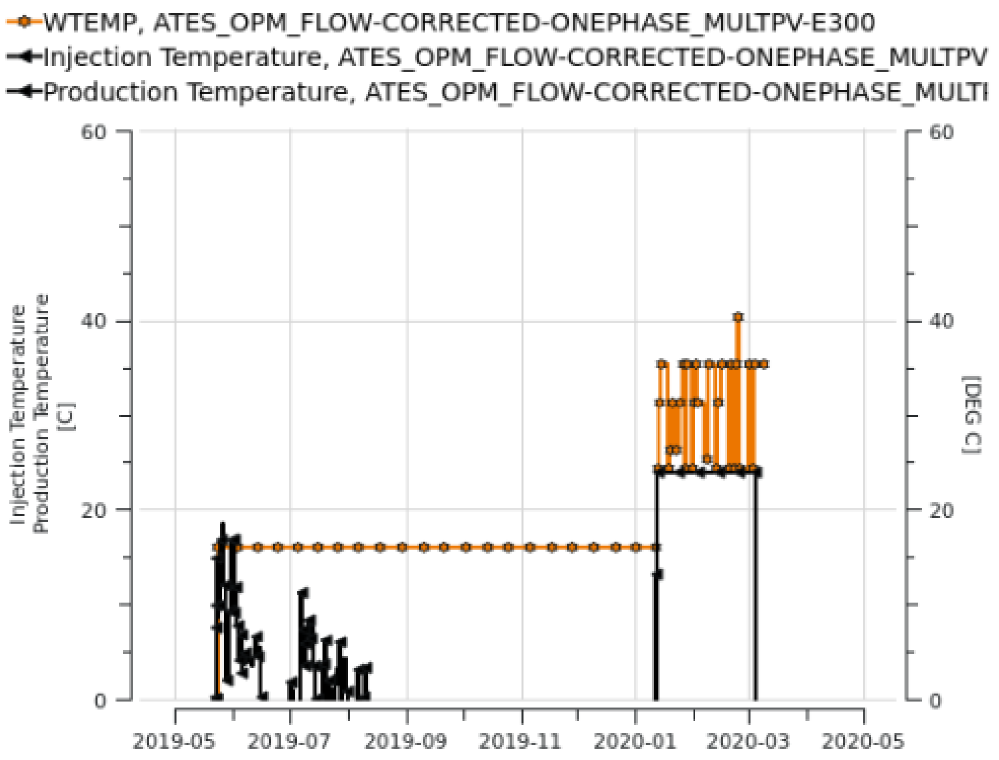
Temperature profiles HT-ATES

OPM-Flow vs. reference thermal simulator

WARM



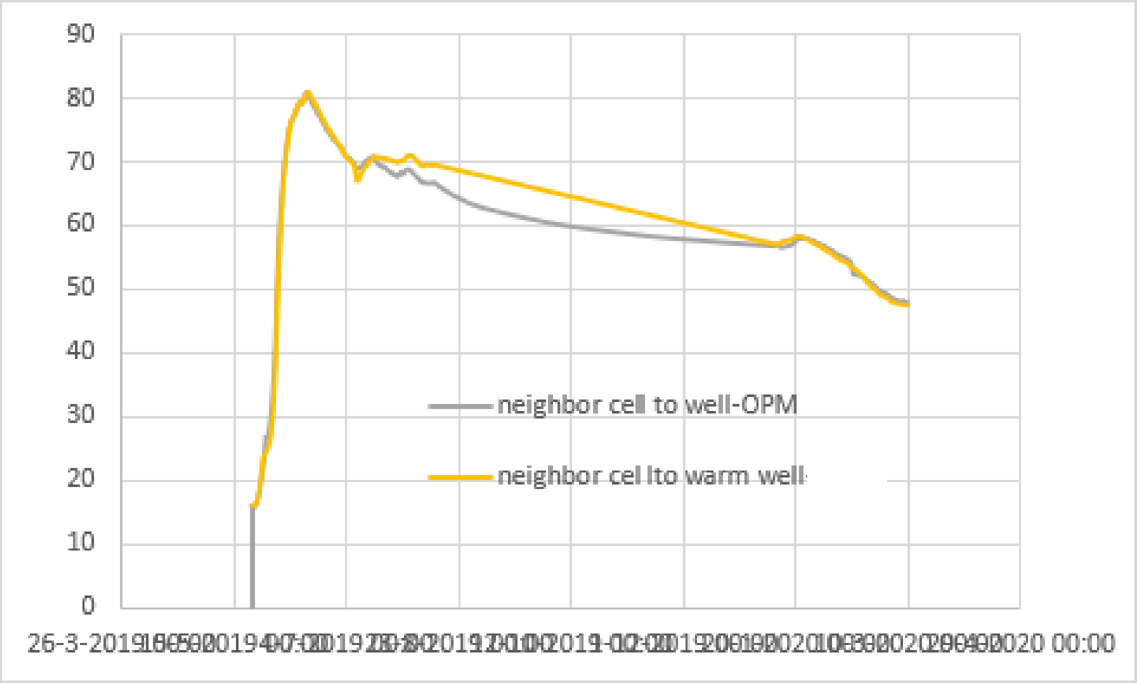
COLD



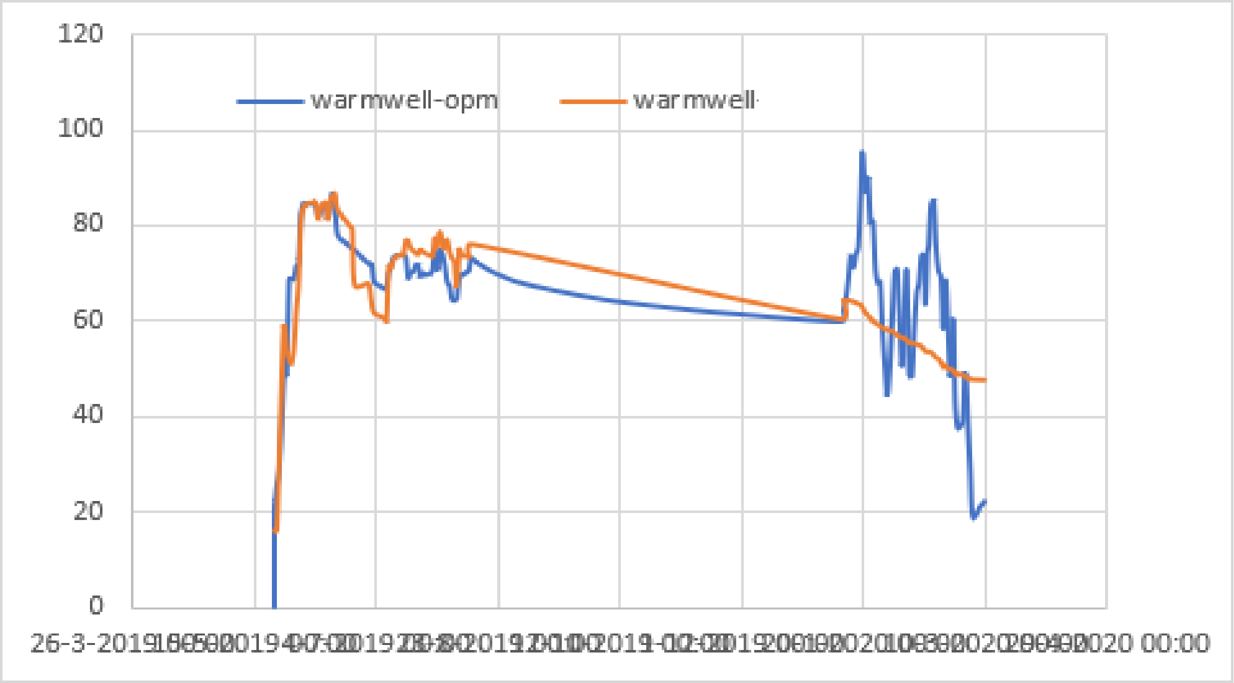
Orange color: Ref. simulator

Temperature changes in grid cells – warm well

106, 75, 6



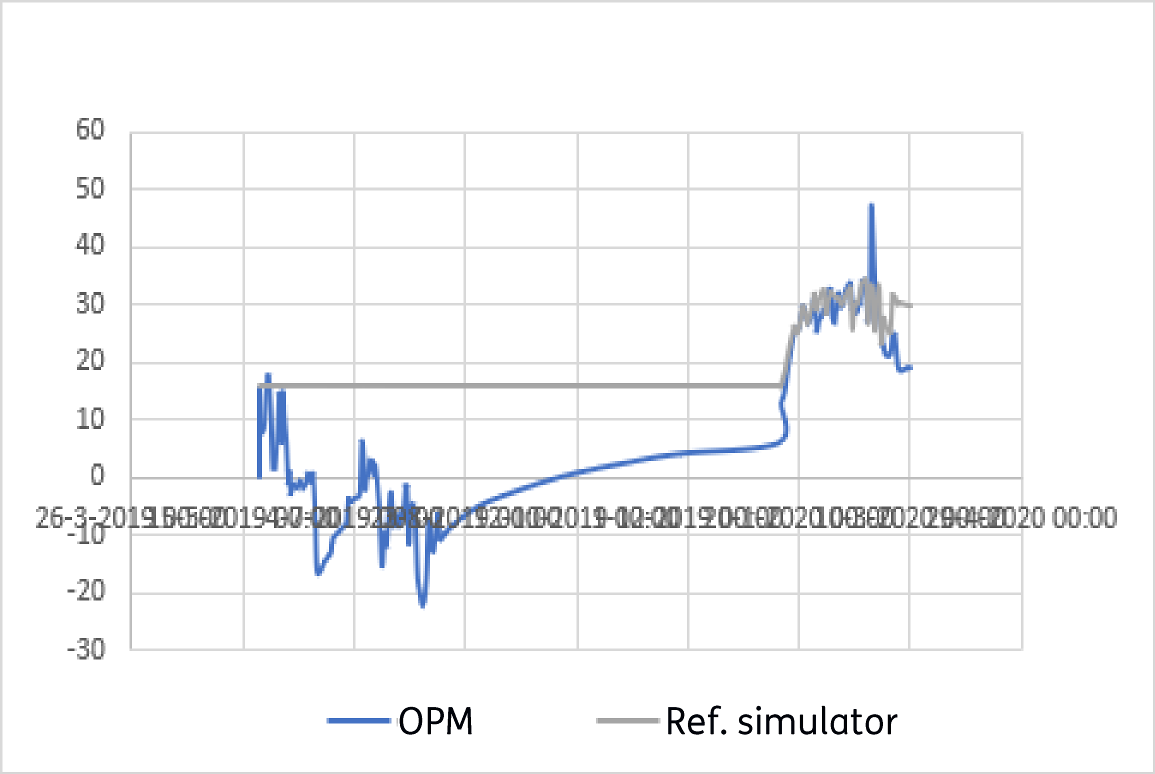
105, 75, 6



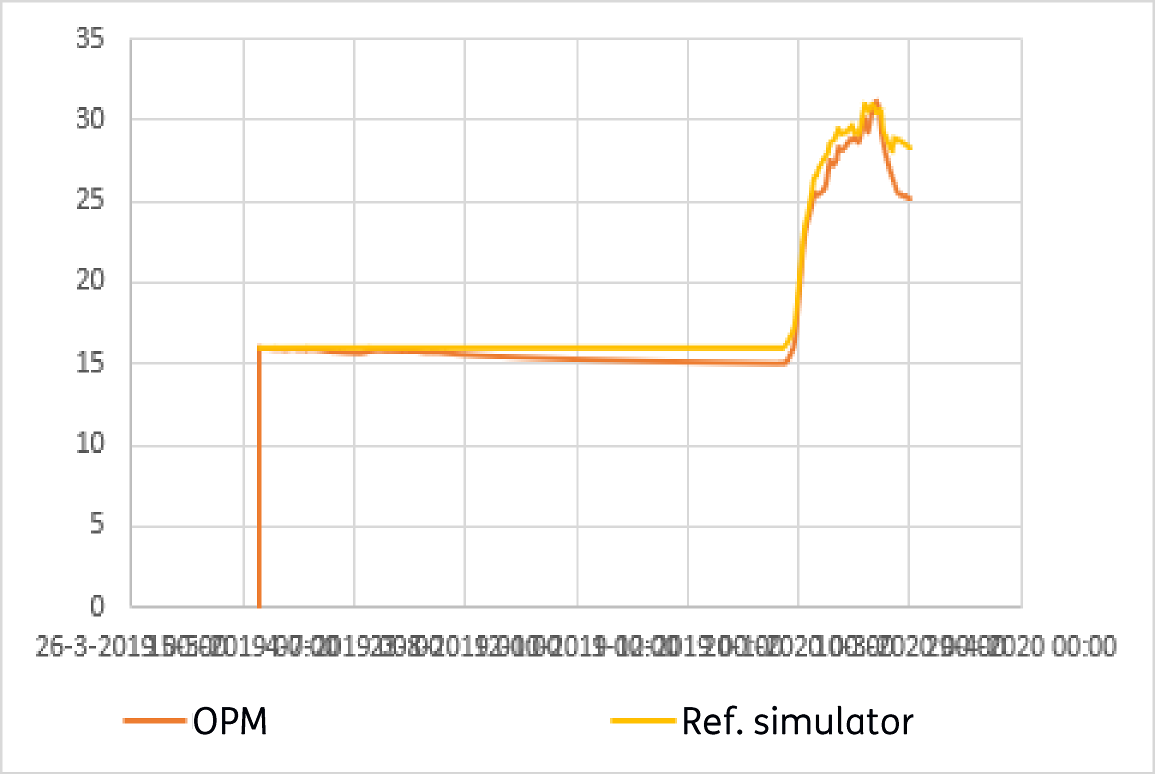
Orange color: Ref. simulator

Temperature changes in grid cells – cold well

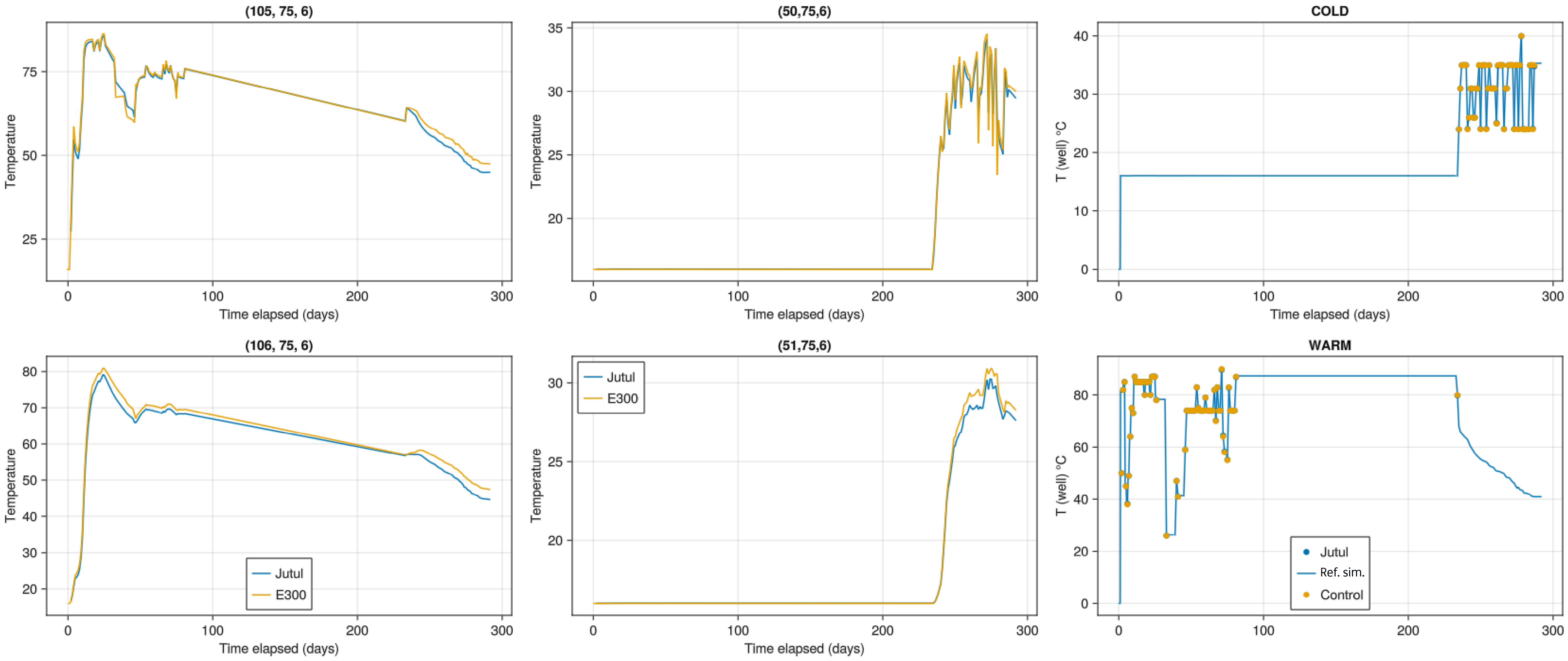
50, 75, 6



51,75,6



Reference thermal simulator vs. Jutul (Olav)



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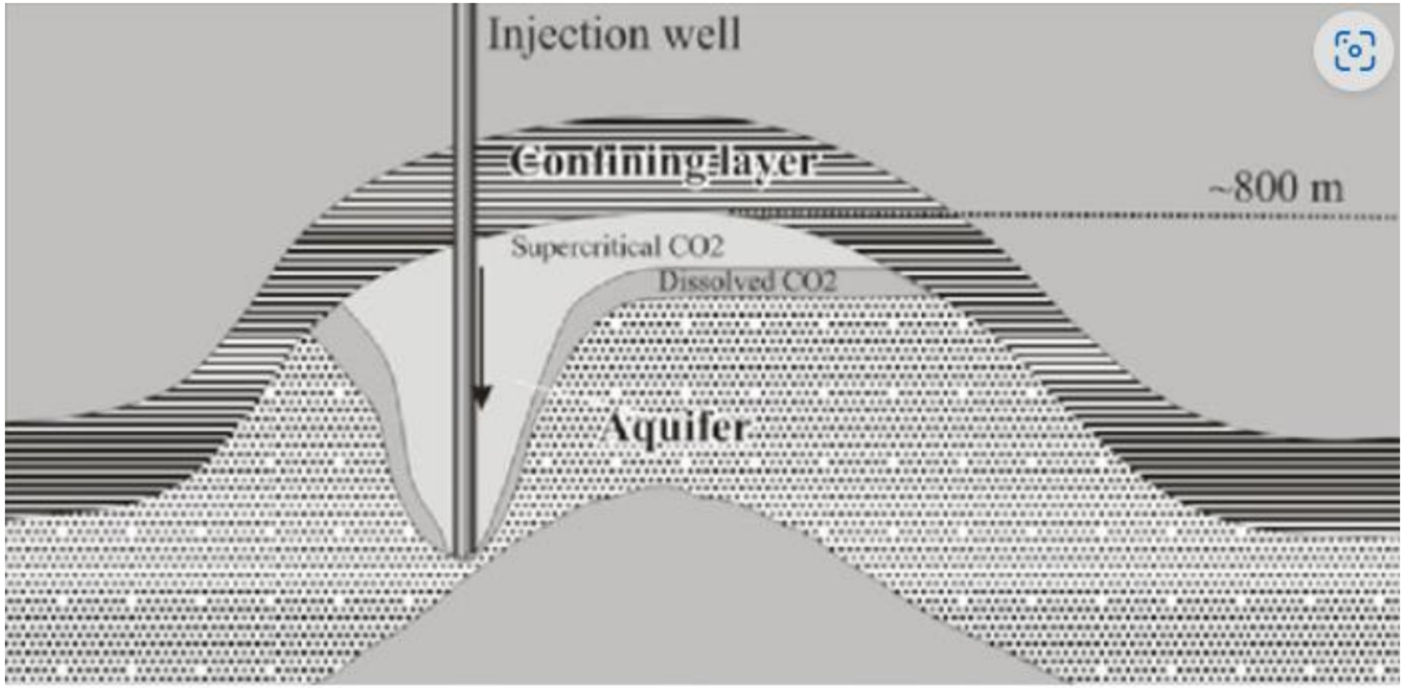
Applications at TNO

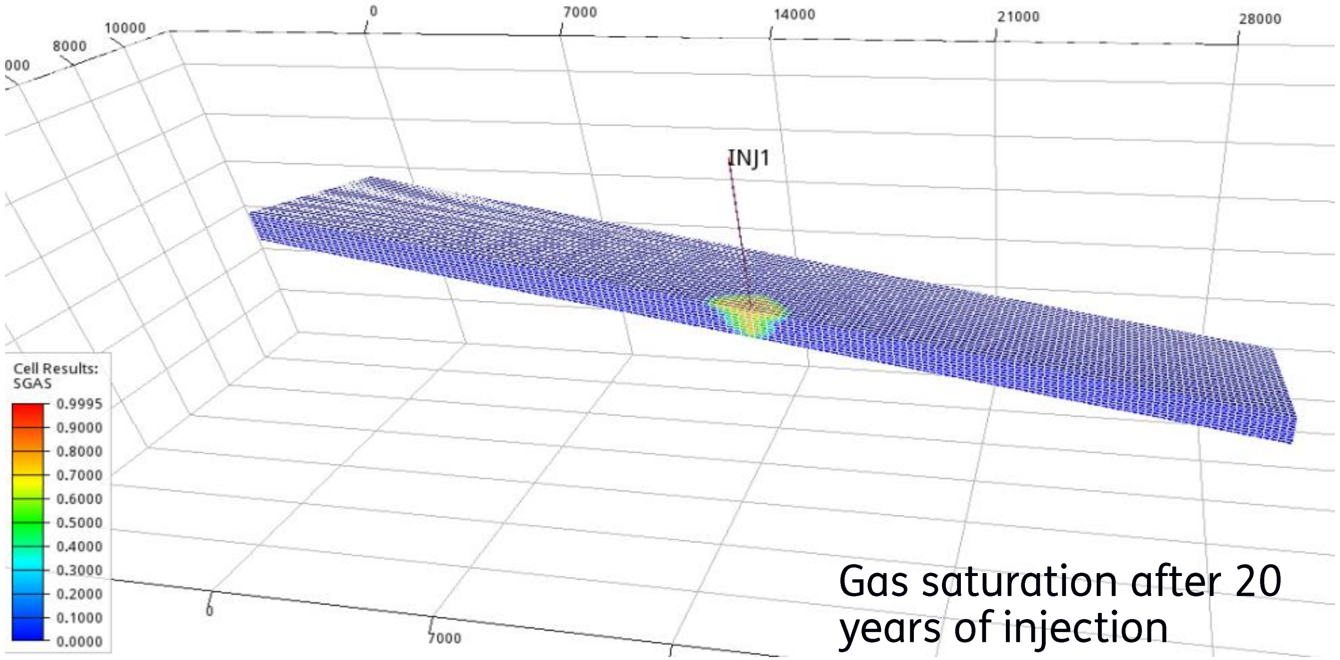
CO_2 storage in Dutch offshore aquifers: capacity study



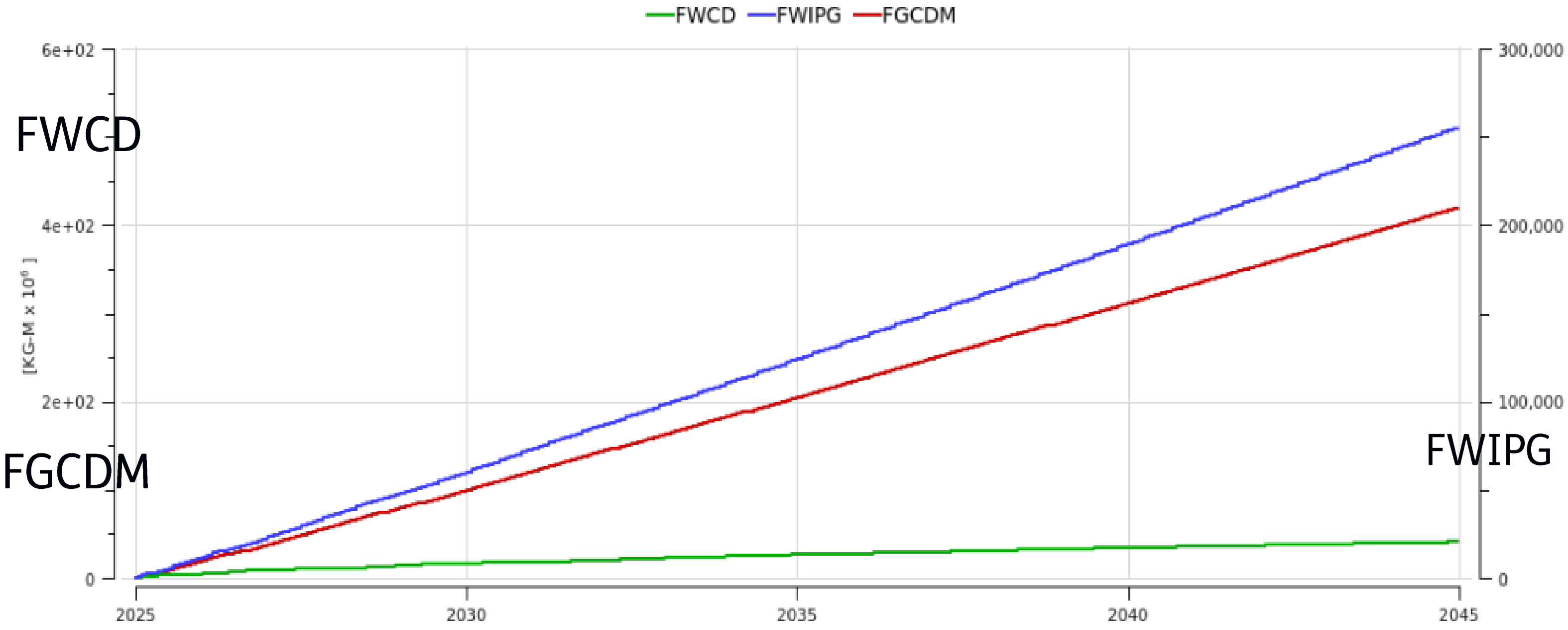
- CO2STORE
- Dissolution trapping
- Dry-out effect
- Residual trapping

Šliaupienė, R. and Šliaupa, S., 2011. Prospects for CO2 geological storage in deep saline aquifers of Lithuania and adjacent territories. Geologija, 53(3).

CO_2 distribution



Gas saturation after 20 years of injection



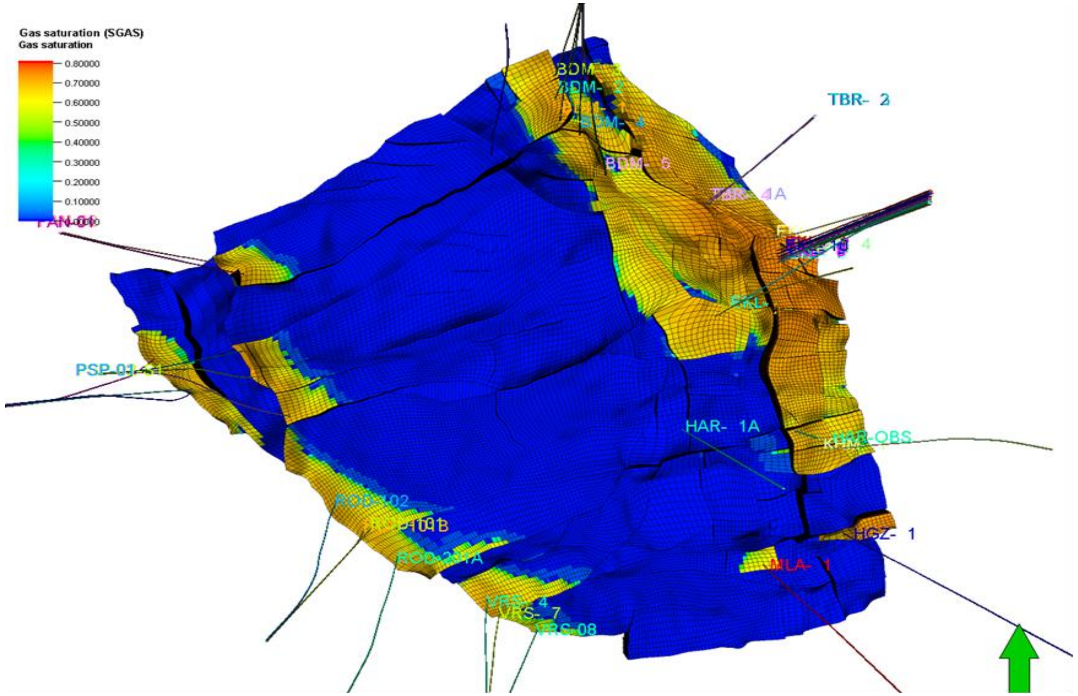
FWCD: CO_2 dissolved in water phase

FWIPG: Water in gas phase

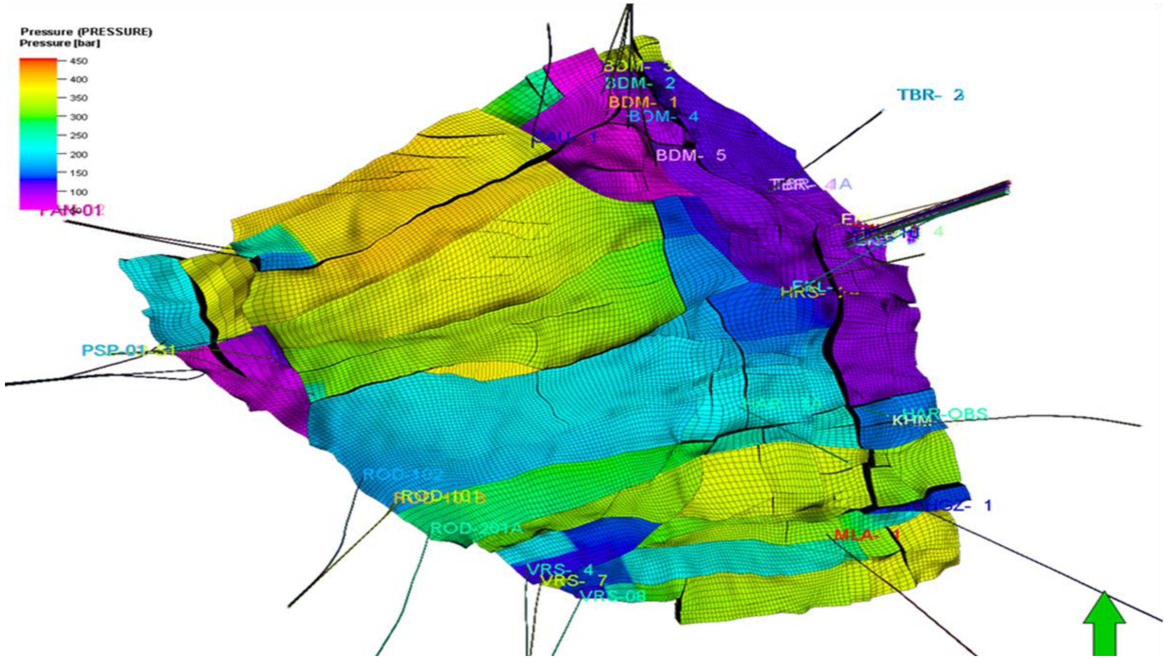
FGCDM: CO_2 dissolved and mobile in gas phase

Applications at TNO

Seismic risk in the southern Lauwerszee Trough aquifer

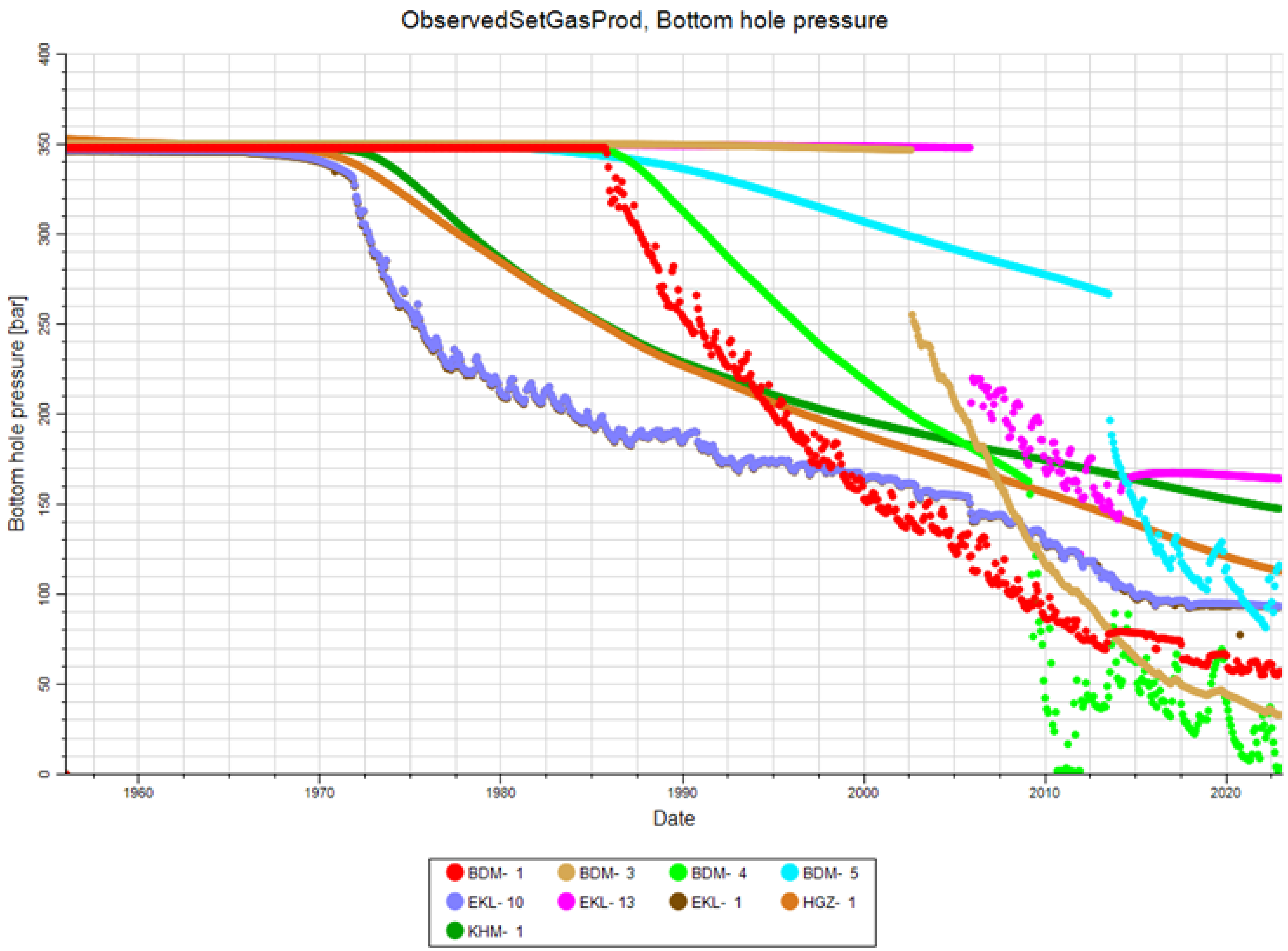


Initial gas saturation distribution



Initial pressure distribution

Varying pressure boundary conditions

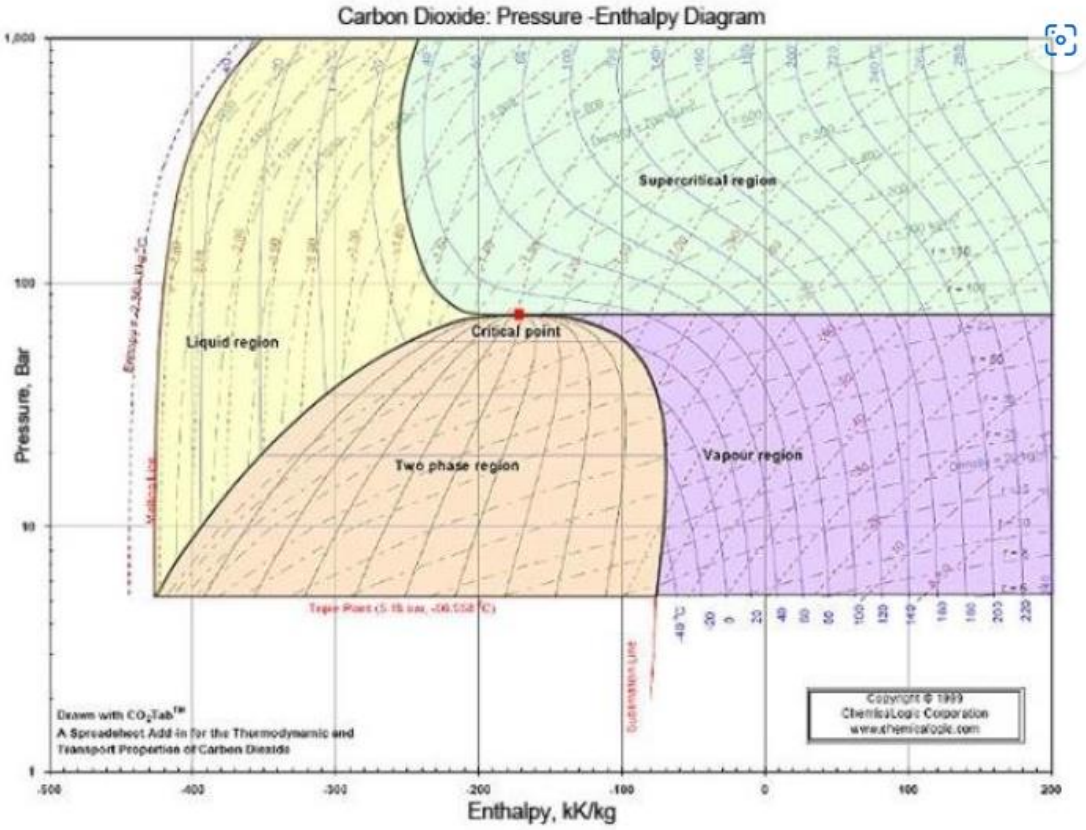


- Gas-water system
- The Groningen field on the east is implemented as a pressure boundary
- Time-varying pressure boundary condition of Groningen implemented via pressure-constrained production wells

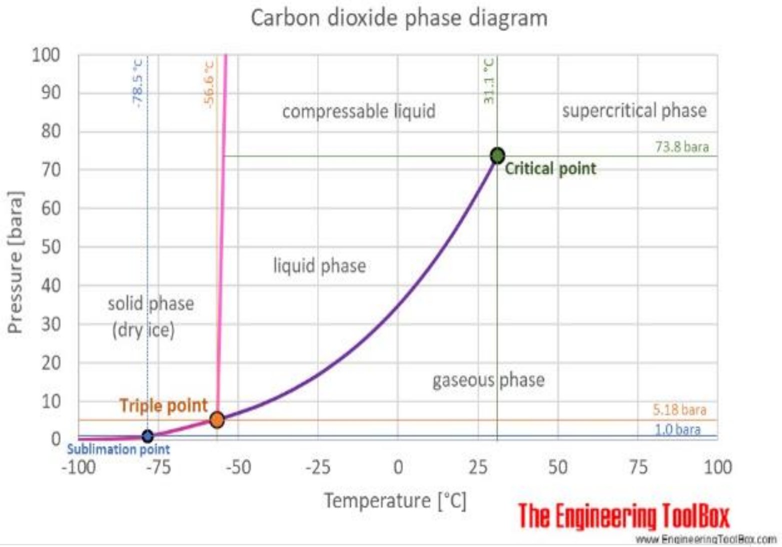
Demand for new features at TNO

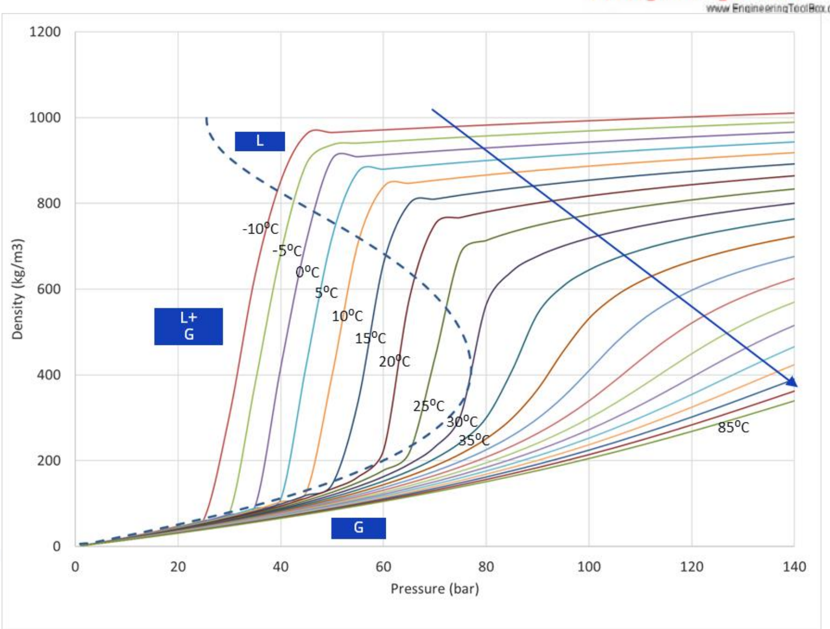
Thermal-compositional with phase change

CO_2 storage in depleted fields



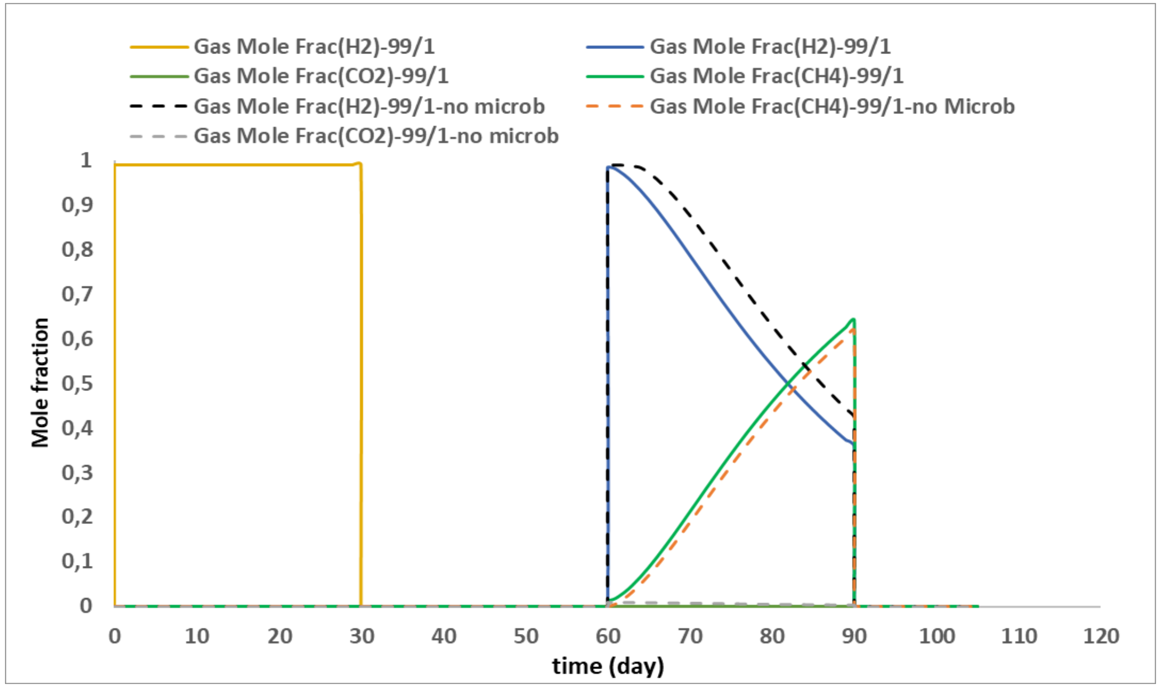
González Díaz, A. (2016). Sequential supplementary firing IN natural gas combined cycle plants with carbon capture for enhanced oil recovery.





H_2 storage with bio-/geochemical reactions

- Fully compositional / different cushion gas
- Bacterial activity (Monod type reaction)
- Geo-chemical reactions (in many applications such as H_2 and CO_2 Storage), coupling with PHREEQC / Reaktoro



- Methanogenic archaea:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

- Sulfate-reducing bacteria:

$$SO_4^{2-} + 5H_2 \rightarrow H_2S + 4H_2O$$

pyrite to pyrrhotite

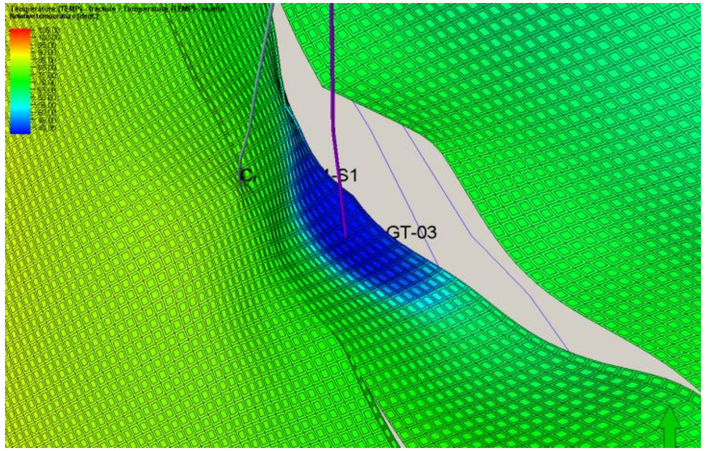
$$FeS_2 + H_2 \rightarrow FeS + H_2S$$

Khoshnevis, N. et. al., 2023, November. Numerical Modeling of Bio-Reactive Transport During Underground Hydrogen Storage–a Benchmark Study. In *The Fourth EAGE Global Energy Transition Conference and Exhibition* (Vol. 2023, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

Geothermal fractured reservoirs

- Many reservoirs exhibit dual-porosity behaviour, in particular in geothermal production.
  - Fractured carbonates like the Californie site in The Netherlands and Balmatt site in Belgium, which are both in the Zeeland Formation of the Carboniferous.
  - Magmatic sites like in Iceland and Los Humeros in Mexico
  - Enhanced Geothermal Systems like in the Upper Rhine Graben
  - Paris basin
- For some applications and conditions, representing the fractured, dual porosity medium as a normal porous medium works well, however this is not true for:
  - Large fracture distance
  - Heterogeneous fracture networks
- In particular this is important to model the distribution of the cold front and the uncertainty, which in turn is crucial for understanding seismicity.
- Progress of cold water front to the producer → prediction of timing of cold water breakthrough

Production well Injection well



Fracture network

Summary and discussion

- LGR
  - Testing and comparing with the fine grid model
- Groningen field
  - Building large-scale dynamic model for numerical performance benchmark purposes
  - Test with OPM
- Applications
  - Improve thermal simulation in OPM: possible to add energy related keywords to summary? (Energy Injection/Production rate, Energy Injection/Production total)
- Demand for new features
  - Thermal-phase change
  - H_2 storage and bio/geochemistry
  - Fractured reservoirs: dual-poro / dual-perm
  - Also needed by other groups?

Thank you
Questions?

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