MODELLING, CALIBRATION, AND OPTIMIZATION OF FTES USING FIMBUL.JL, WITH EXAMPLES FROM REAL CASES

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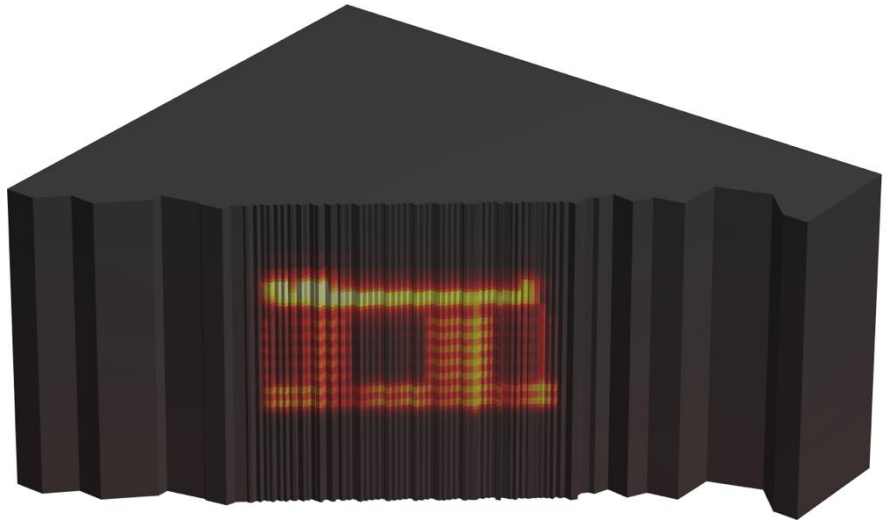
Fracture Thermal Energy Storage (FTES) Online Workshop 2026
IEA Geothermal Heating and Cooling Working Group, May 26, 2026

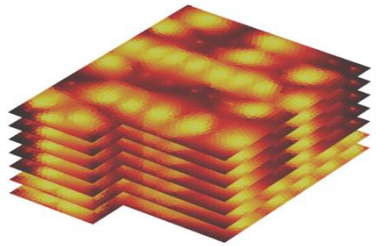
GHOST DigiT

Geological High-temperature Optimized Simulation Technology – Digital Twin

KSP-N: Collaborative and knowledge-building Project
Project for Industry (RCN, project 344540)

GHOST DigiT aims to develop digital twin technology for real-time monitoring and prediction of the subsurface to enable optimal design, operation, and management of geothermal storage in a dynamic energy system





SINTEF Wessel Energi

LKAB KVITEBJØRN VARME

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Julia scientific software ecosystem – Applied computational science group

Darcy-scale porous media flow
Oil & gas, CO_2 sequestration, H_2/gas storage, etc.

```
using Pkg; Pkg.add("JutulDarcy")
```

Geothermal energy
Easy setup for common applications, models and analysis

```
using Pkg; Pkg.add("Fimbul")
```

MIT license

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Cornerstone Julia framework for
differentiable
finite-volume simulation

```
using Pkg; Pkg.add("Jutul")
```

Battery Modelling Toolbox
Continuum modelling of electrochemical devices

```
using Pkg; Pkg.add("Battmo")
```

Modelling of Carbon Capture
Pressure/temperature swing adsorption of CO_2

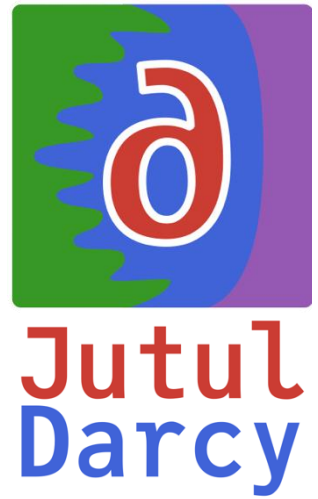
```
using Pkg; Pkg.add("Mocca")
```

Wait – another simulator?

Fimbul is a geothermal simulation toolbox

- **Focus on use-cases** – implements functionality for setting up, simulating, and analyzing common geothermal energy applications
- Implements modelling functionality **specific to geothermal energy**
- Ambition: **lean codebase** – easy to maintain, easy to use

Fimbul is built on top of JutulDarcy[1]



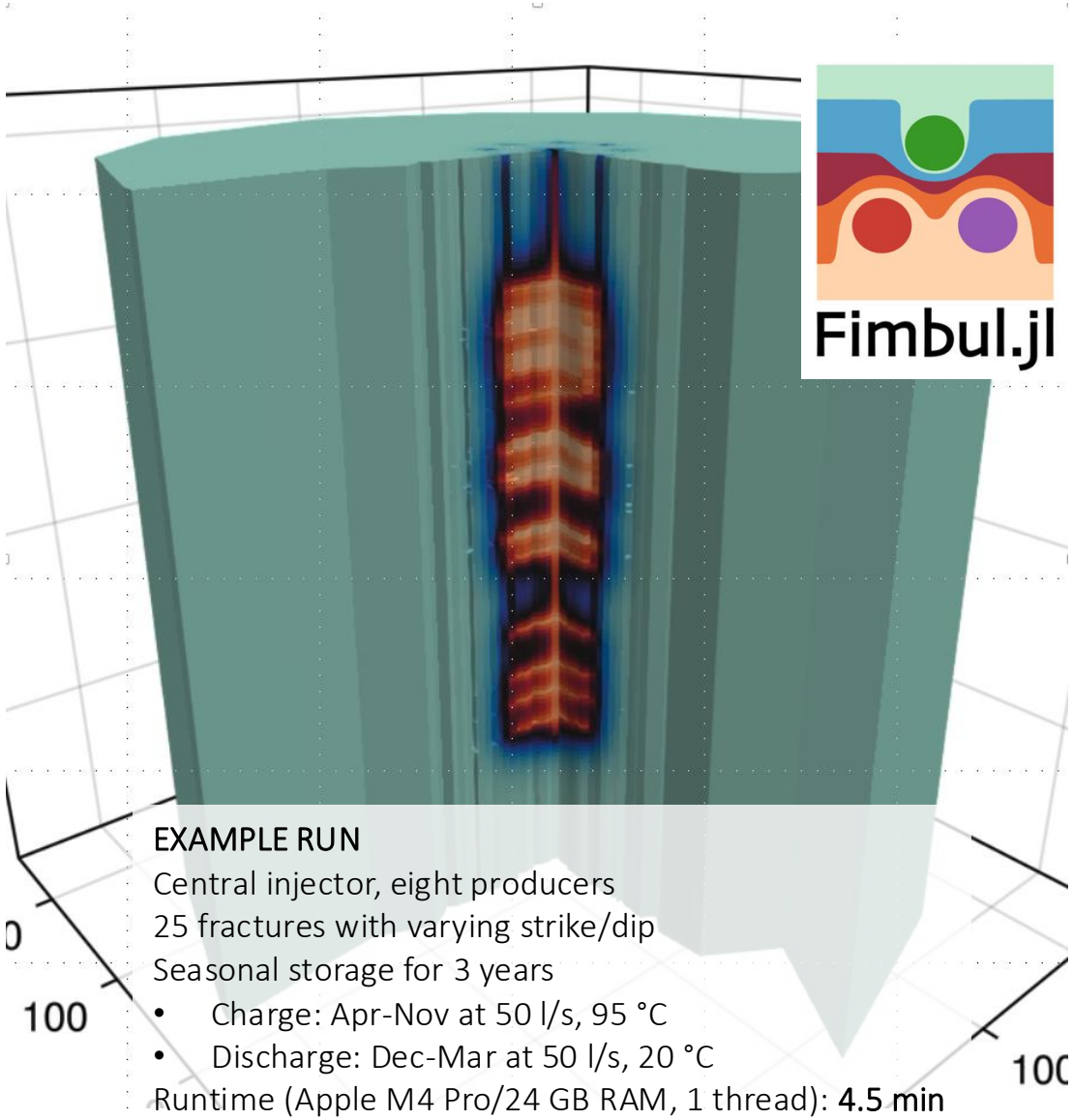
- Darcy-scale porous media flow simulator written in Julia
- Built from the bottom up using **automatic differentiation (AD)**
  - Computation of gradients/sensitivities, seamless integration with machine-learning workflows
  - Enables using very efficient optimization algorithms for **parameter calibration/control optimization**
- **Supports multiple input formats** (Eclipse/Intersect, Gmsh, MRST, etc.)
- MPI parallel w/ BoomerAMG and threads, GPU support through CUDA + AMGX

[1]Møyner (2025), DOI: 10.1007/s10596-025-10366-6

FTES in Fimbul

- Brand new functionality for fracture modelling (discrete fracture model)
- Setup function for typical configuration

```
function ftes(well_coordinates::Vector{Matrix{Float64}}, fractures::AbstractDict;
    depths = nothing,
    matrix_properties = Dict{Symbol, Any}(),
    fracture_properties = Dict{Symbol, Any}(),
    rate_charge = missing,
    rate_discharge = missing,
    temperature_charge = convert_to_si(95.0, :Celsius),
    temperature_discharge = convert_to_si(20.0, :Celsius),
    producer_bhp_fraction = 0.1,
    charge_period = ["April", "November"],
    discharge_period = ["December", "March"],
    utes_schedule_args = NamedTuple(),
    mesh_args = NamedTuple(),
    info_level = 0,
    )
```



EXAMPLE RUN

Central injector, eight producers

25 fractures with varying strike/dip

Seasonal storage for 3 years

- Charge: Apr-Nov at 50 l/s, 95 °C
- Discharge: Dec-Mar at 50 l/s, 20 °C

Runtime (Apple M4 Pro/24 GB RAM, 1 thread): **4.5 min**

PARAMETER CALIBRATION

SETUP

Injector circled by eight producers at 25 m radius

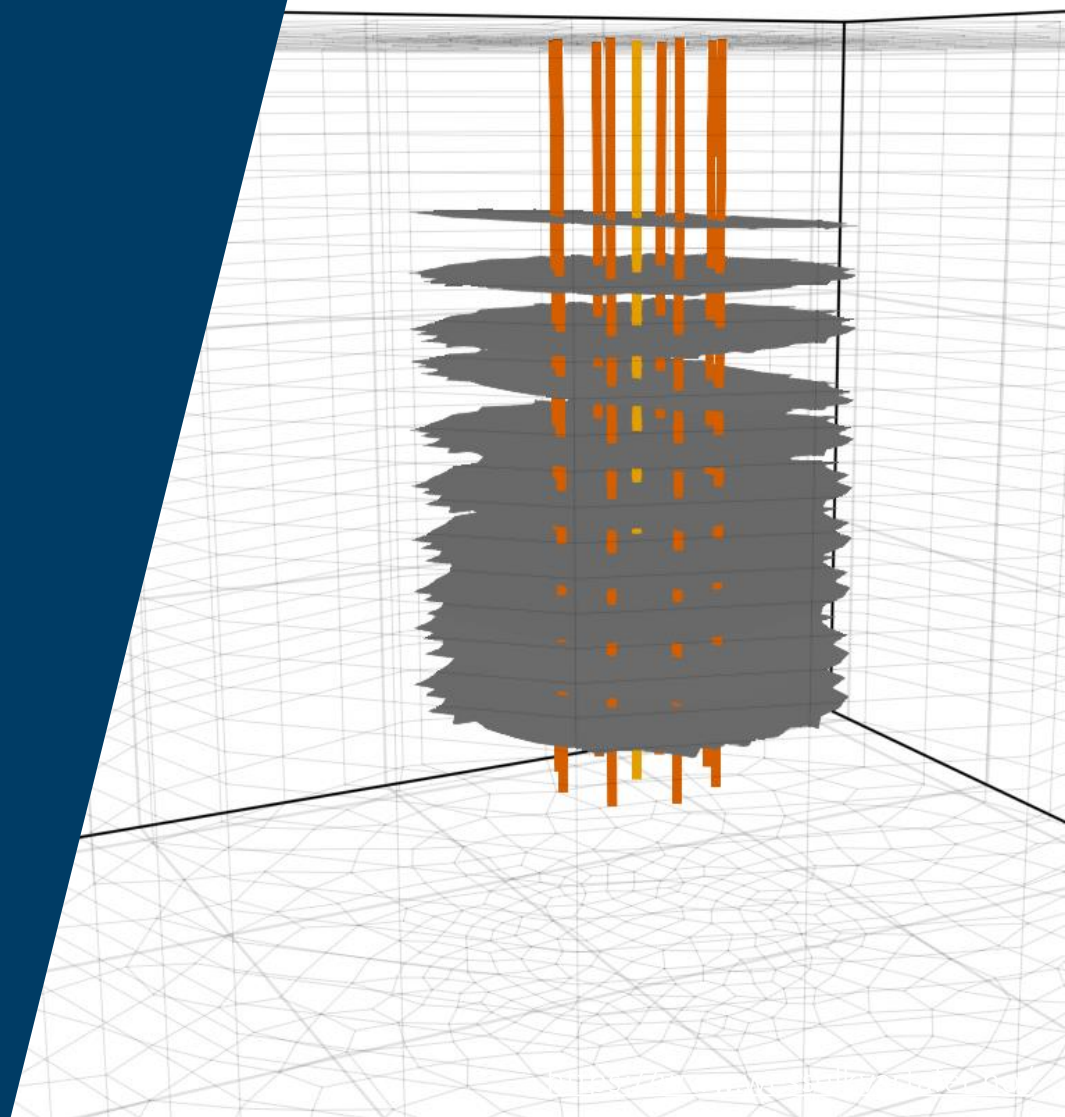
Ten evenly spaced fractures centered in injector, 55 m radius

GOAL

Set up and simulate reference model

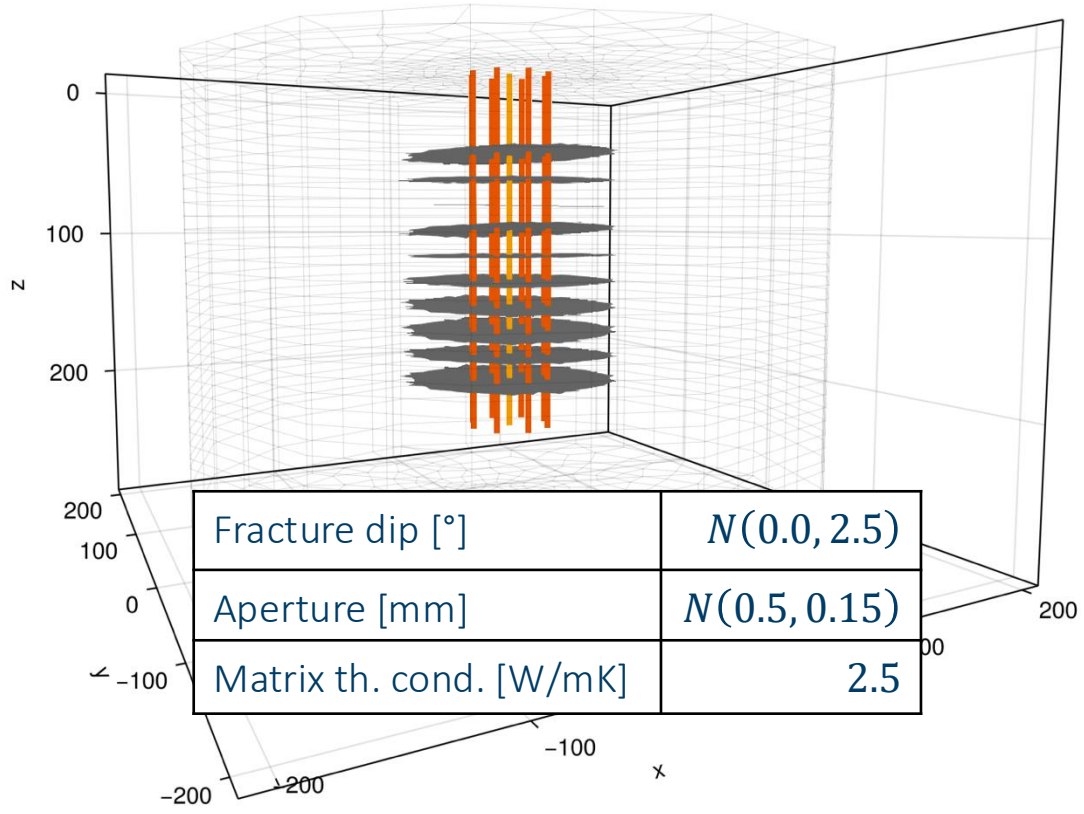
Calibrate idealized model to reference using gradient-based optimization

- Adjoint-based optimization with LBFGS



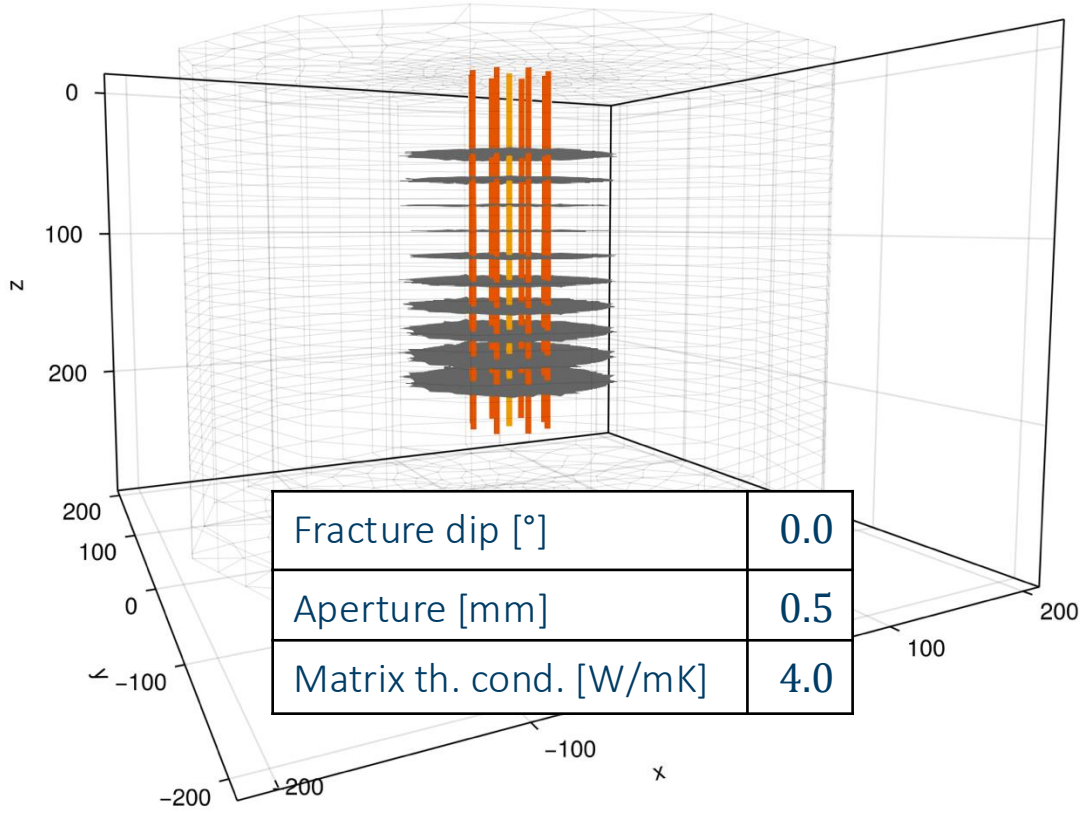
FTES calibration

REFERENCE MODEL



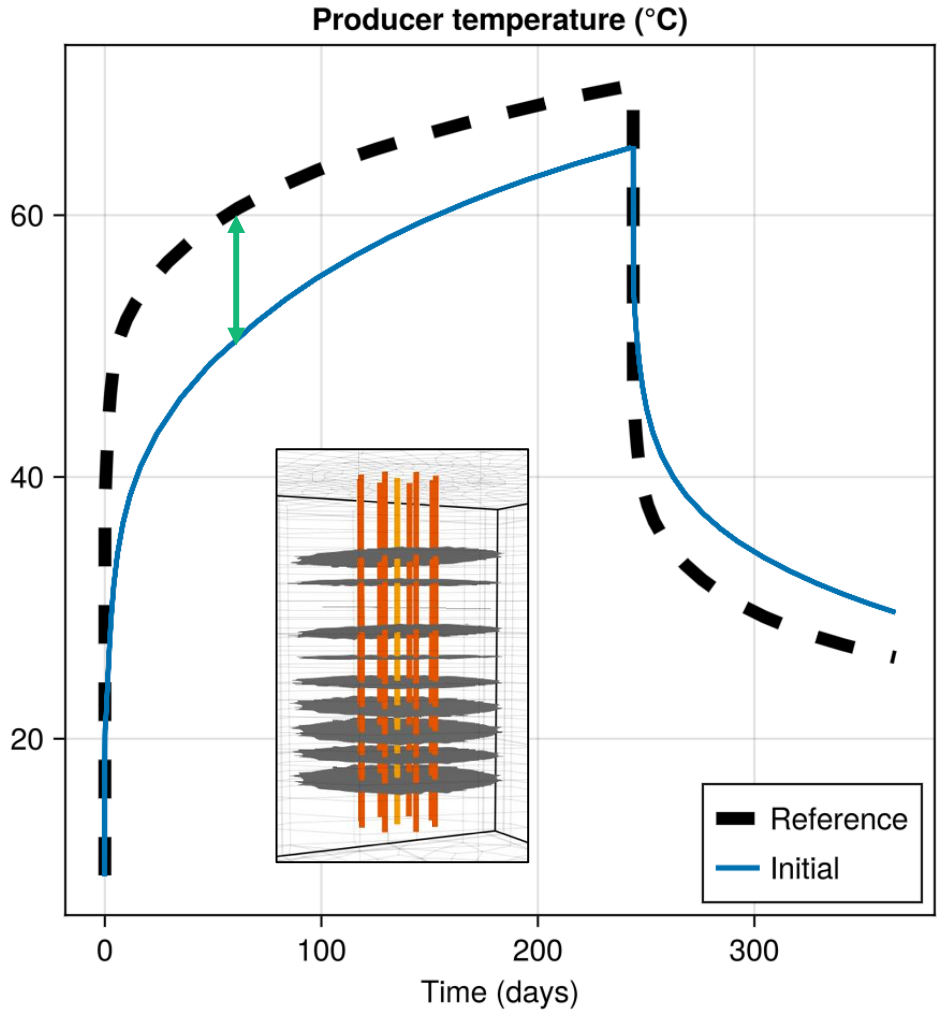
Fracture dip [°]	$N(0.0, 2.5)$
Aperture [mm]	$N(0.5, 0.15)$
Matrix th. cond. [W/mK]	2.5

IDEALIZED MODEL



Fracture dip [°]	0.0
Aperture [mm]	0.5
Matrix th. cond. [W/mK]	4.0

FTES calibration

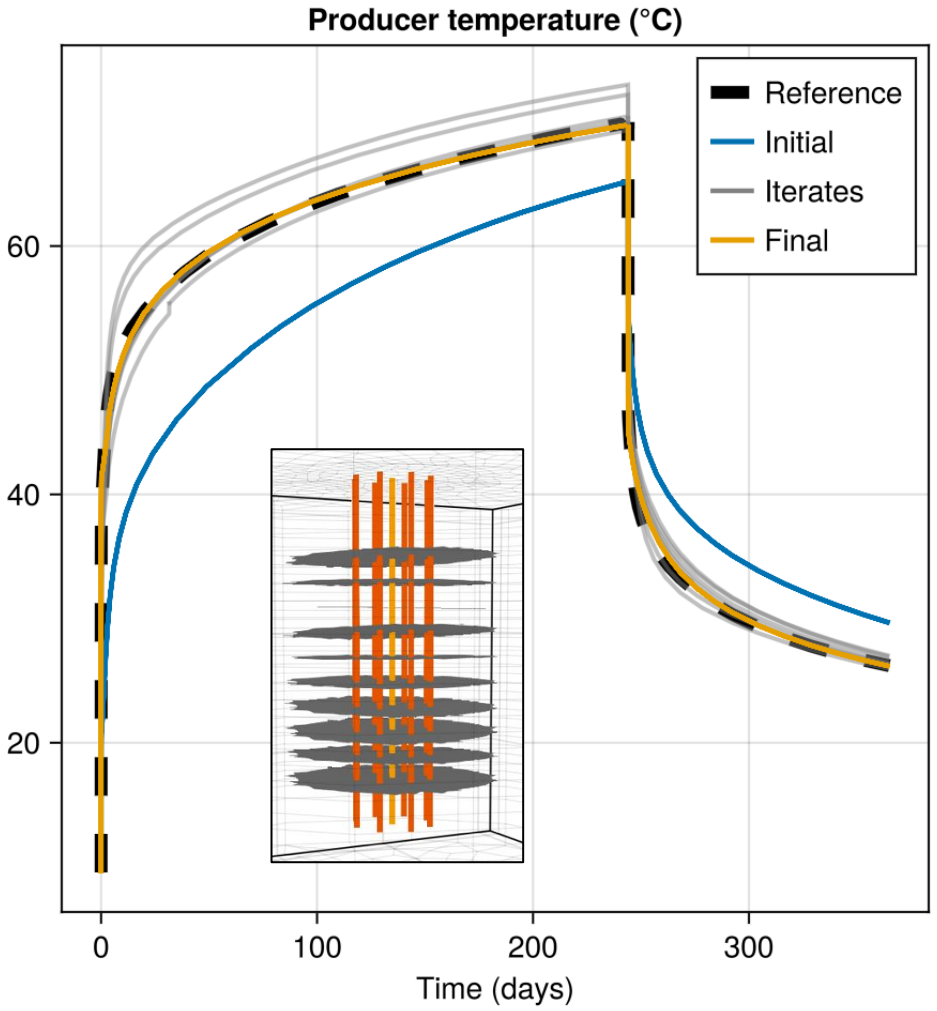


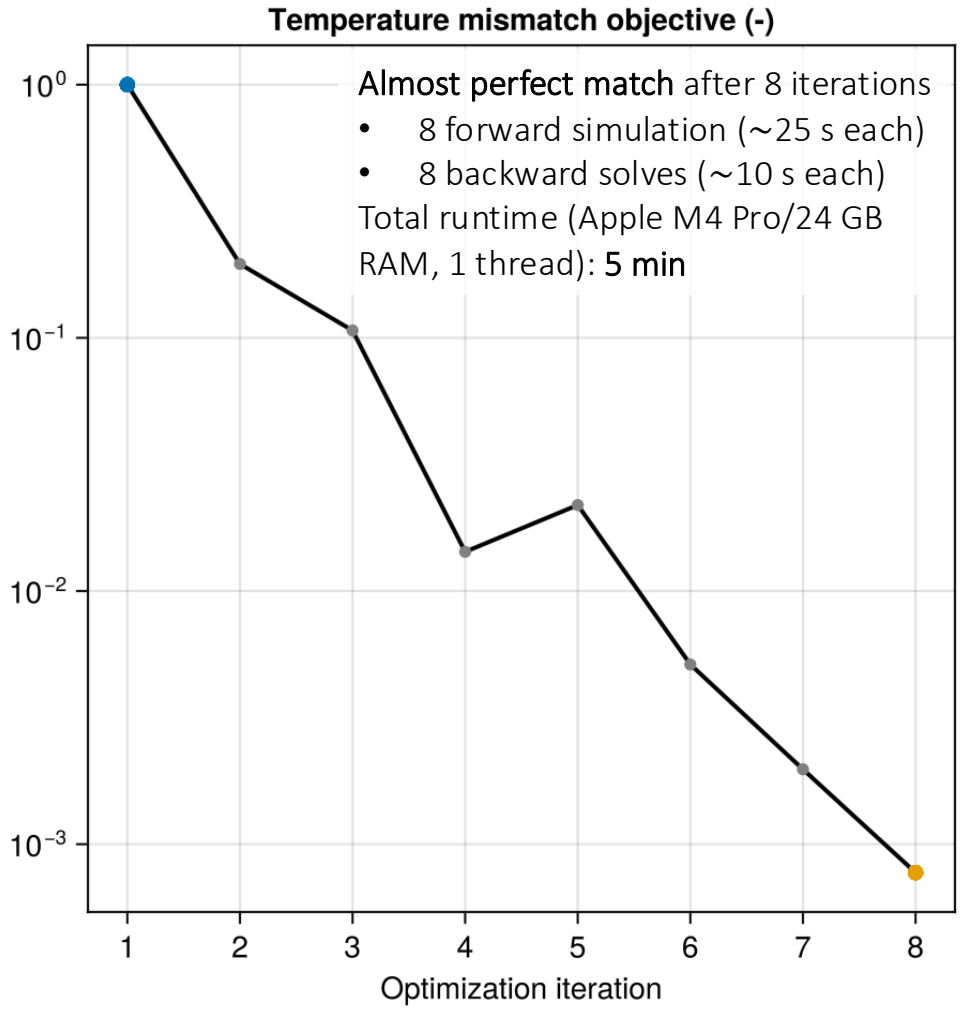
Calibrate parameters of idealized model so that mismatch with reference production temperature is minimized:

$$\frac{1}{t_{\text{tot}}} \sum_n (T^n_{\text{Ref}} - T^n_{\text{Id}})^2 \Delta t^n$$

Parameter	Min	Max
Aperture [mm]	0.1	1.0
Matrix th. cond. [W/mK]	1.0	4.0

FTES calibration





WESSELKVARTALET

FRACTURE THERMAL ENERGY STORAGE

Underneath parking garage – 97 wells coupled in eight groups

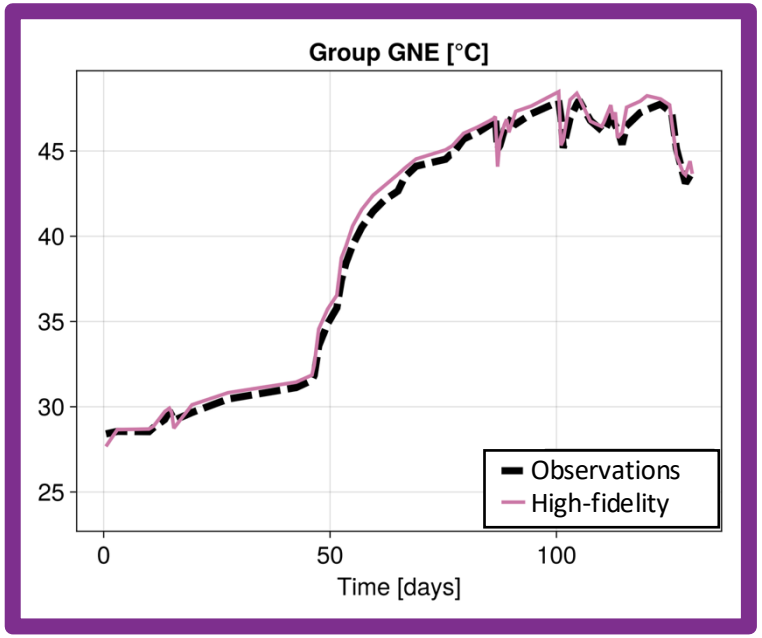
Gravel layer: 2m, rapid discharge of heat
Accumulator (fractured bedrock): 18 m, long-term storage

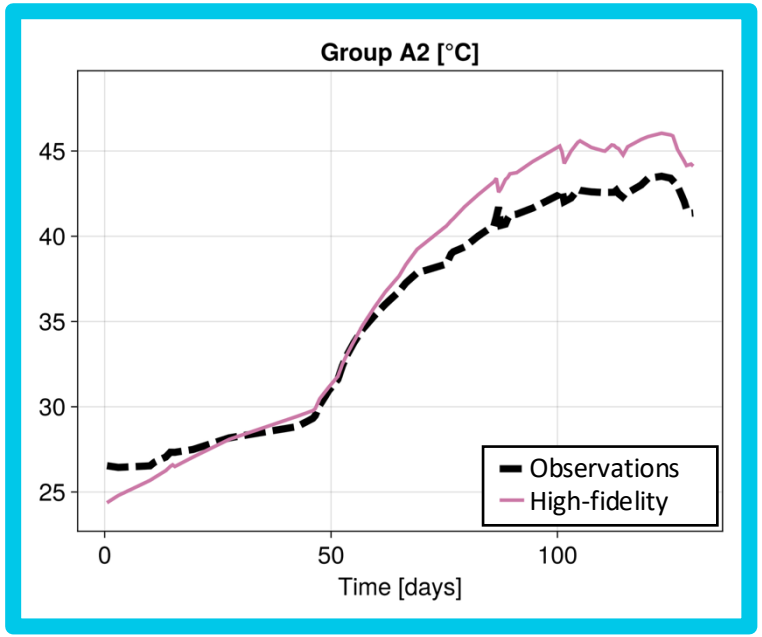
OPERATION

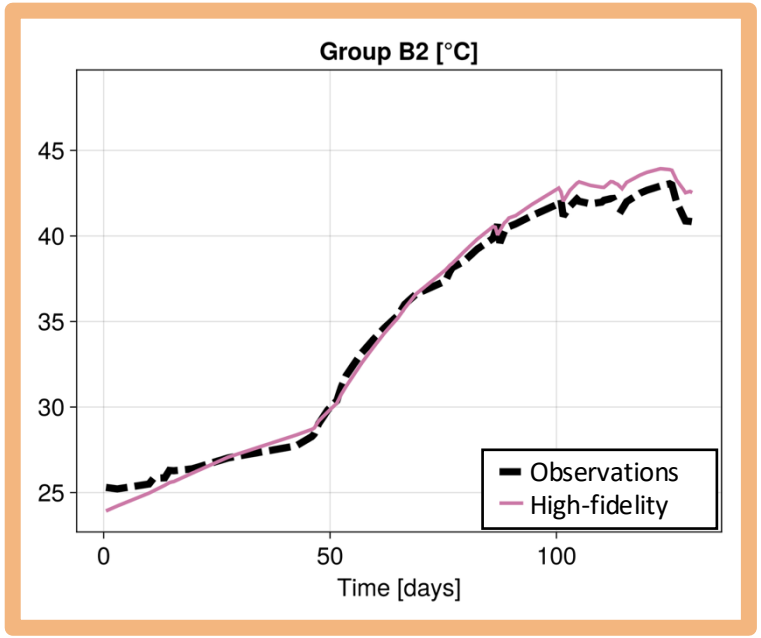
Residential heating: 30 000 m^2/Deicing: 30 000 m^2 city streets

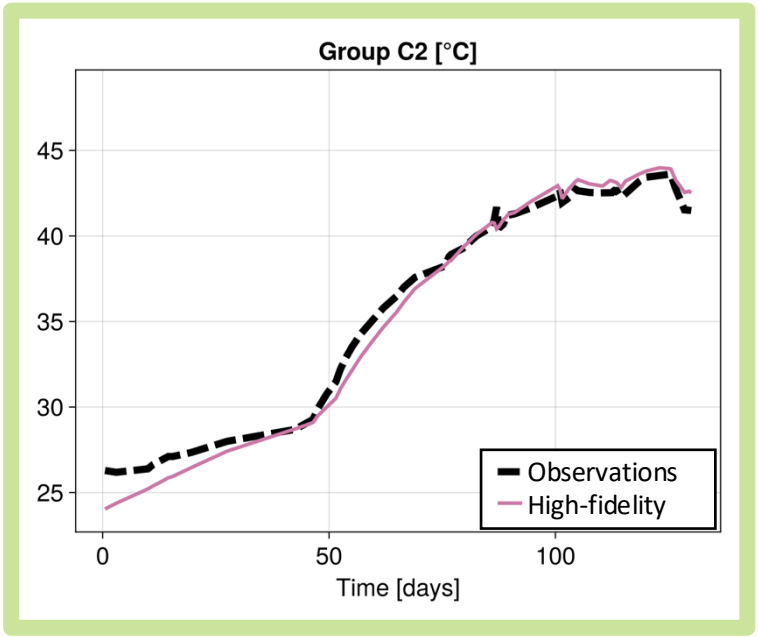
Operational targets:

- Storage @ 40 °C, heated from 20 °C
- Yearly production: 12 GWh/year, Peak: 13.5 MW

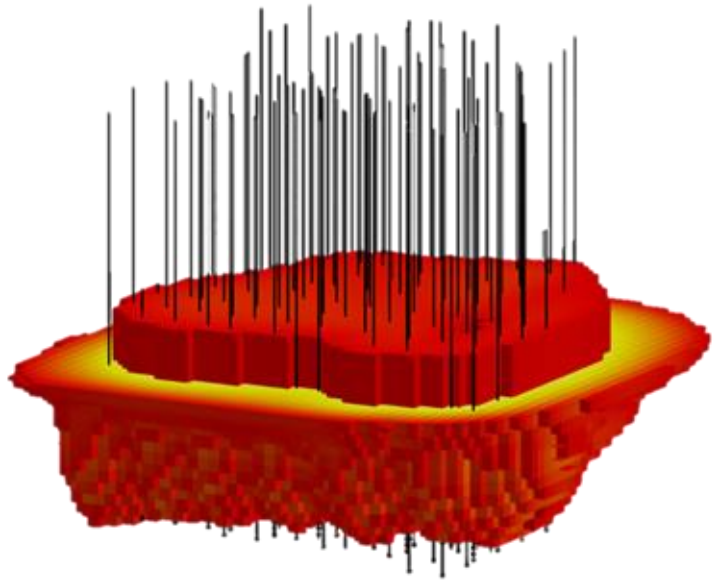








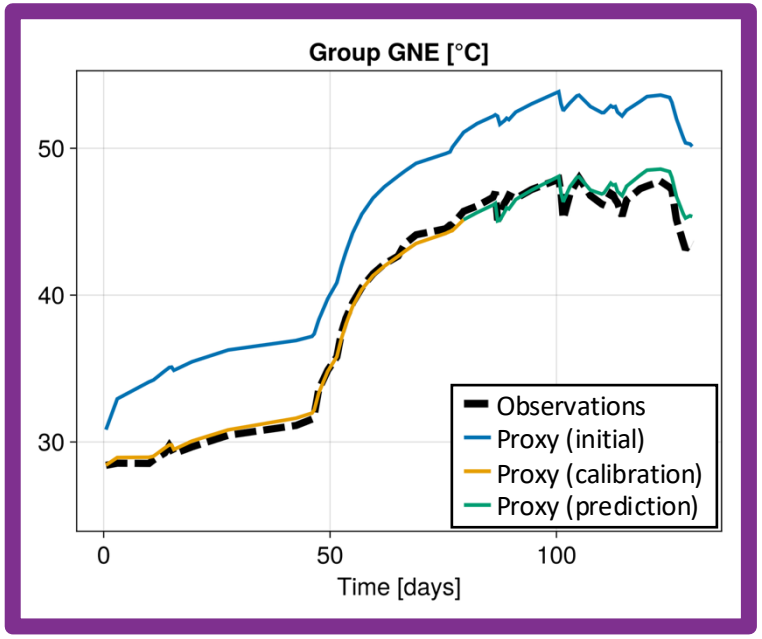
HIGH-FIDELITY MODEL

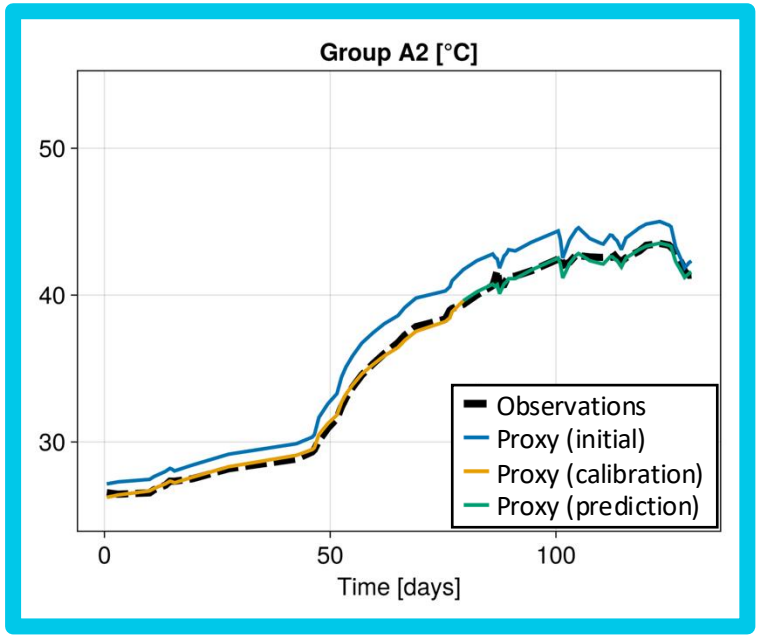


# dofs:	166 153	Sim. time: 2.57 h
# parameters:	1 433 414	

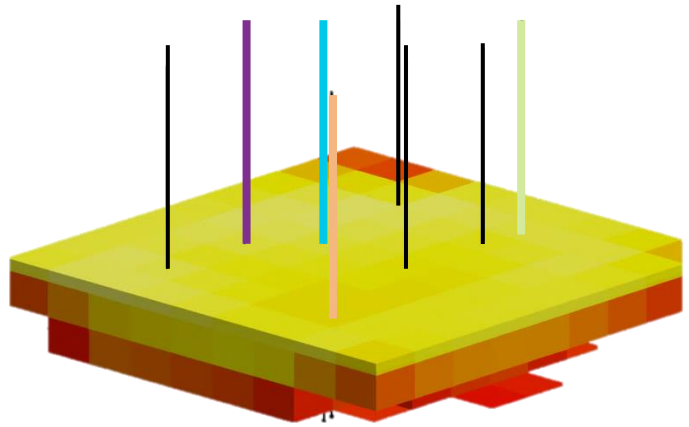
All 97 wells represented
Ten horizontal fractures intersecting all wells

No calibration – proposed parameters give **adequate match** with observed production temperatures in all well groups

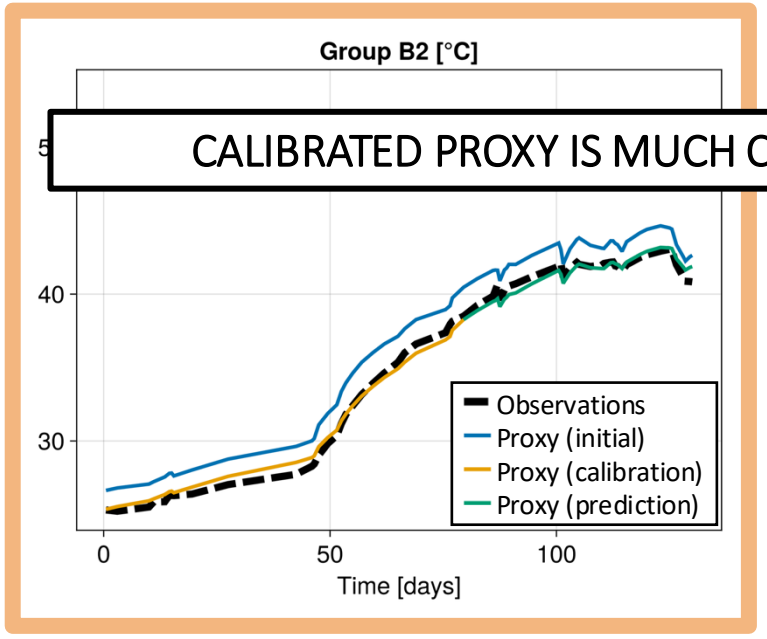


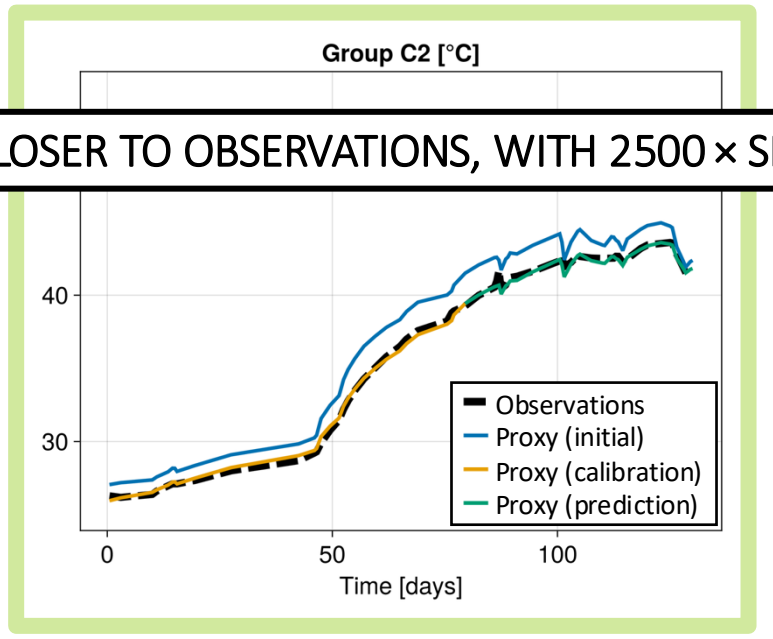


PROXY MODEL



# dofs:	1 644	Sim. time: 3.6 s
# parameters:	13 686	





CALIBRATED PROXY IS MUCH CLOSER TO OBSERVATIONS, WITH 2500× SPEEDUP TO HIGH-FIDELITY MODEL

Only well groups represented (8 in total)

Initial proxy shows poor match

Calibrate to observed temperatures:

$$\frac{1}{t_{\text{tot}}}\sum_{n}\sum_{\substack{\alpha=\text{GNE},\\ \text{A2,B2,C2}}}\left(T_{\alpha}^{n,\text{obs}}-T_{\alpha}^{n,\text{PX}}\right)^{2}\Delta t^{n}$$

Reproduces calibration data

Excellent prediction of unseen data

Fimbul.jl

*We gratefully acknowledge the partners of **GHOST-DigiT** and the **Research Council of Norway** for funding this research, and our colleagues at **SINTEF Digital** for insightful discussions and feedback.*

Documentation

GET abstract

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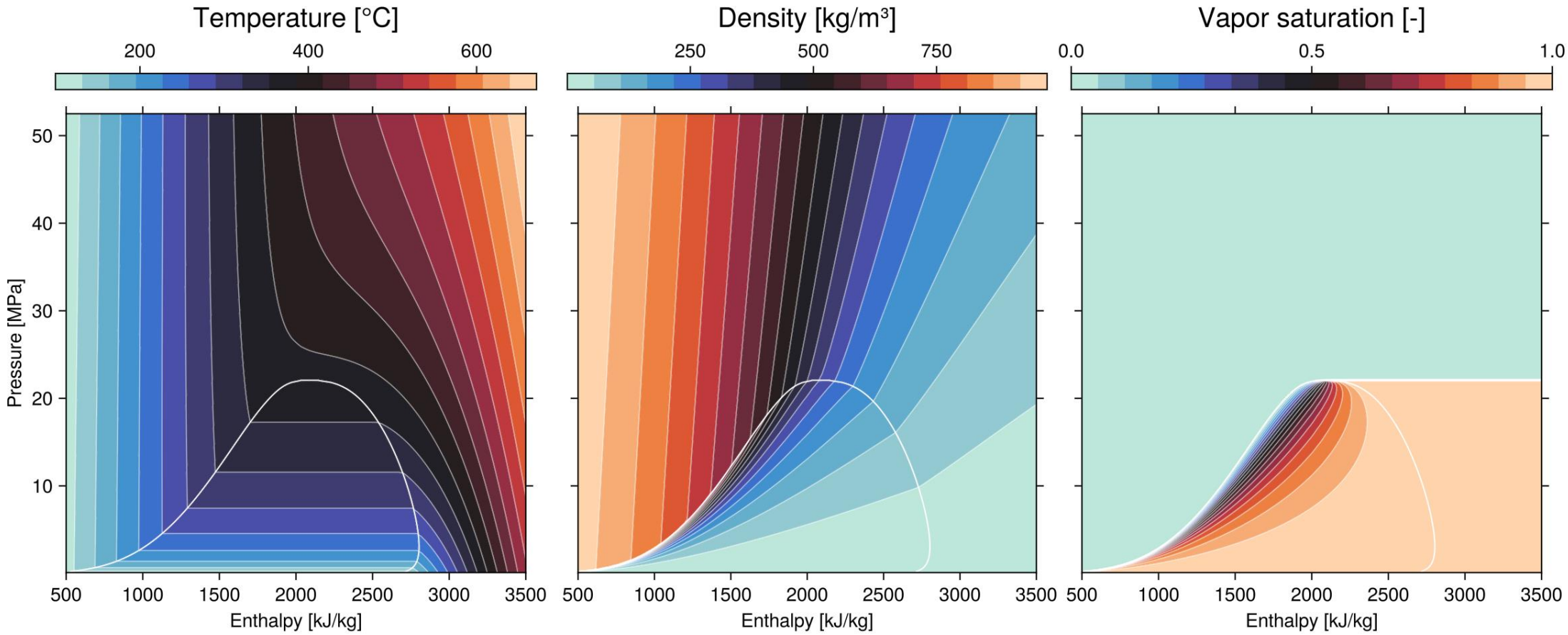
strene

SINTEF

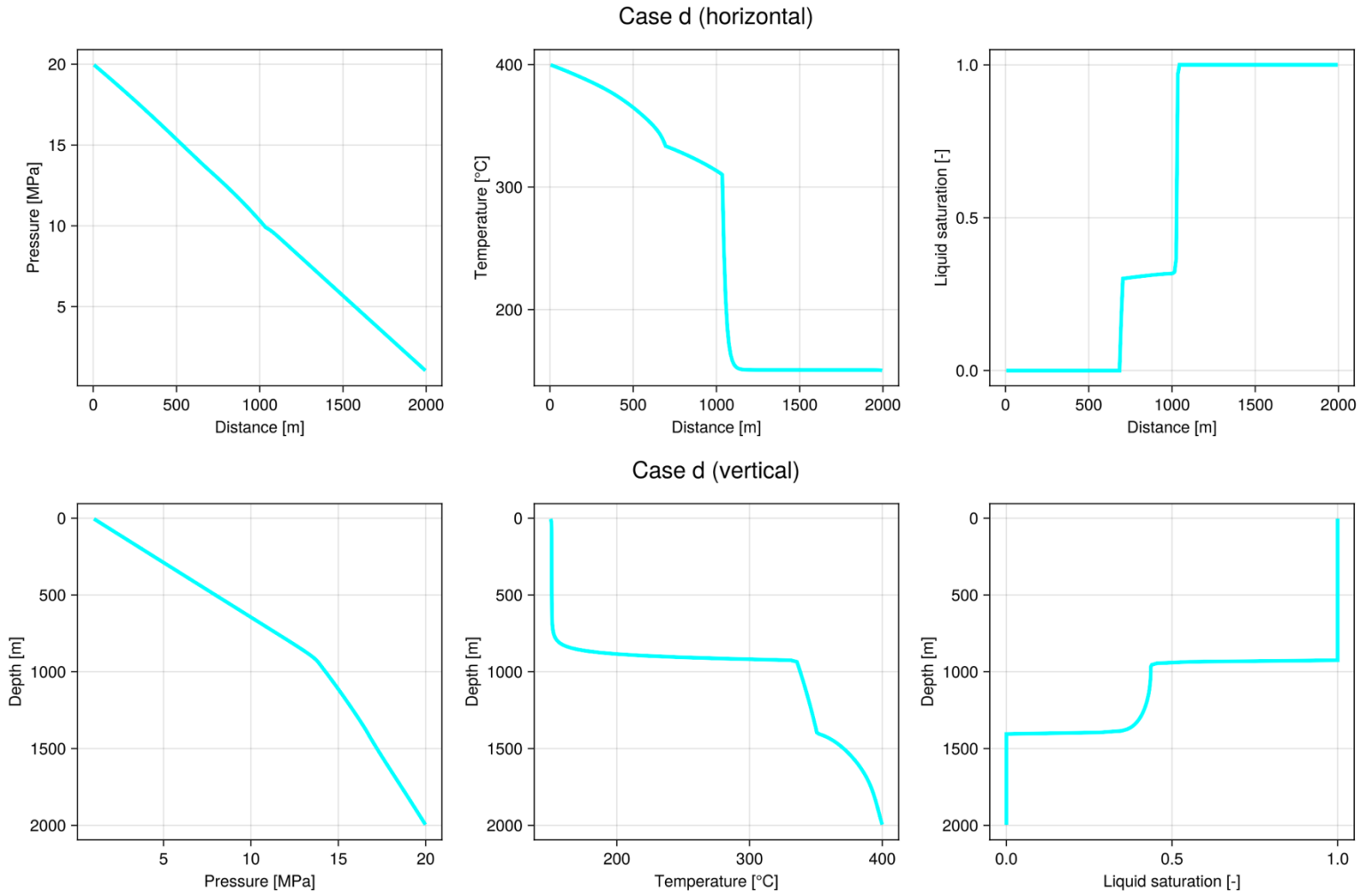
Technology for a better society

Coming soon: high-enthalpy support



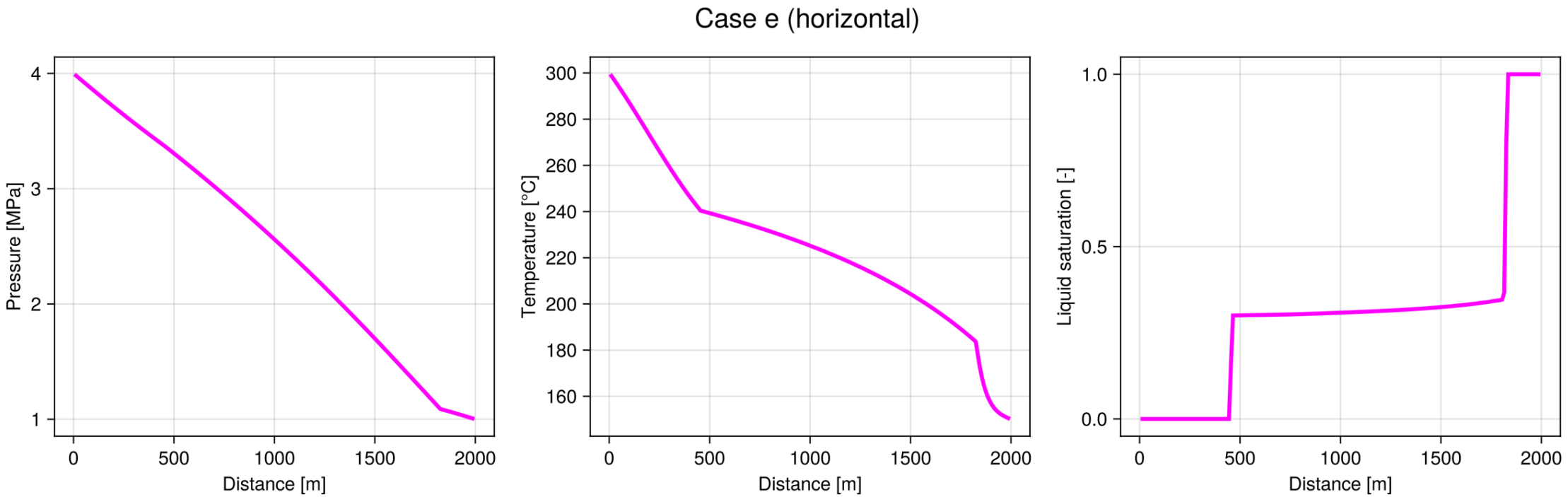
PVT tables generated using CoolProp (https://github.com/CoolProp/CoolProp.jl)

Coming soon: high-enthalpy support



Benchmark from Weis et al. (2014), DOI: 10.1111/gfl.12080

Coming soon: high-enthalpy support



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