# DIGITAL TWINNING OF UNDERGROUND THERMAL ENERGY STORAGE SYSTEMS

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GeoEnergy 2025, Bergen, November 12, 2025

# Applied Computational Science

## SINTEF Digital, Mathematics and Cybernetics

19 permanent researchers (PhDs in mathematics/physics/geophysics), plus affiliated PhD and master students

*Expertise: Development of advanced computational methods and algorithms in efficient, reliable, and robust scientific software for complex modeling and simulation challenges*

### Research and Industry in Synergy

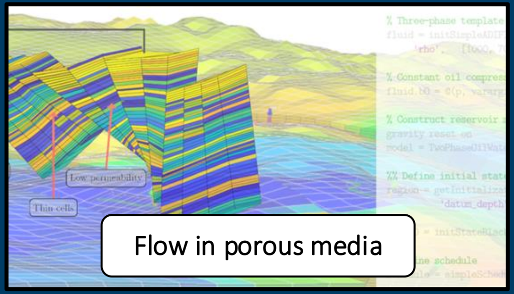
Combining academic depth with practical understanding of industrial needs

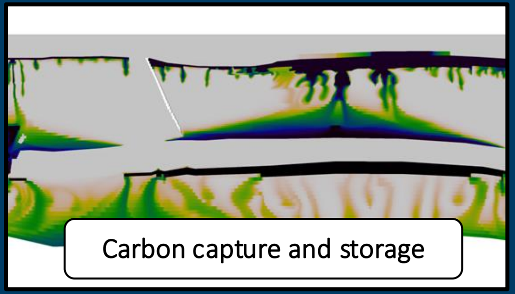
### Open Source and Real Impact

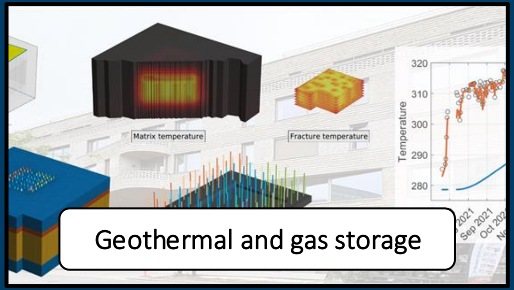
OPM Flow is in operational use, and MRST has been used in over 180 MSc and PhD theses and 400 scientific publications from outside the group

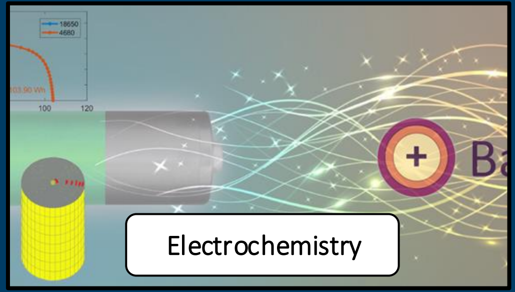
### Strategic Innovation

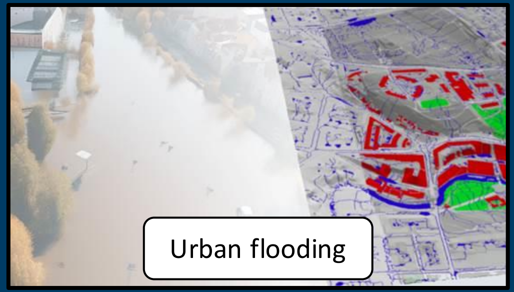
We research next-generation simulation tools, including data-driven methods and agentic AI, differentiable simulators, and quantum computing

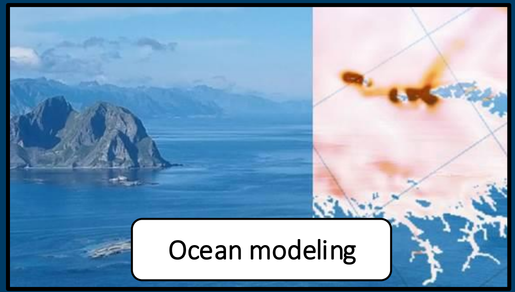

Flow in porous media

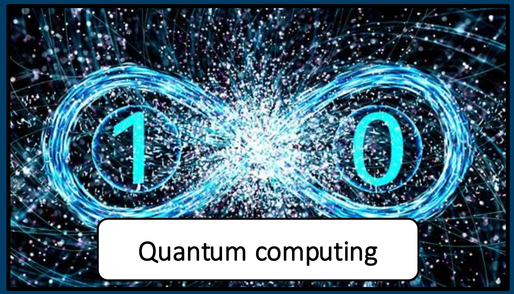

Carbon capture and storage

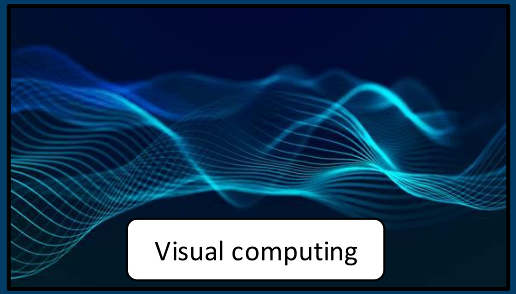

Geothermal and gas storage


Electrochemistry

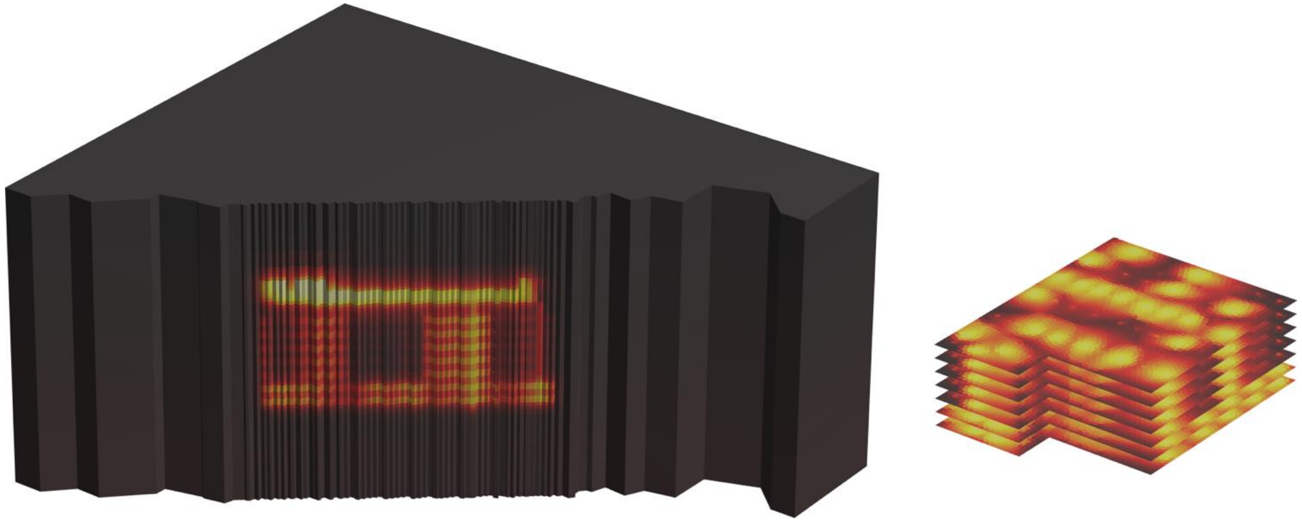

Urban flooding


Ocean modeling


Quantum computing


Visual computing

# 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
asplan viak
Ruden AS

# WESSELKVARTALET

## FRACTURED THERMAL ENERGY STORAGE

Underneath parking garage – 97 wells coupled in eight groups

Water circulated through manufactured fracture network to allow heat conduction to/from bedrock

## OPERATION

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

Operational targets:

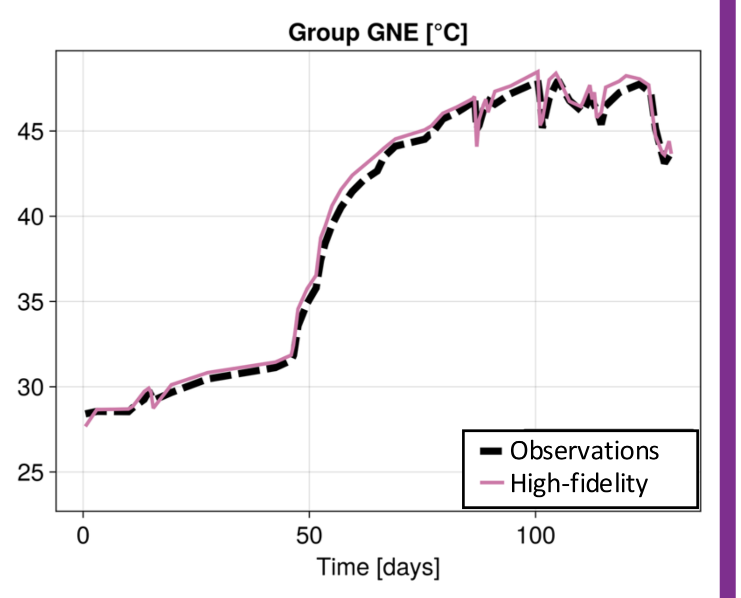
- Storage @ 40 °C, heated from 20 °C
- Yearly production: 12 GWh/year, Peak: 13.5 MW

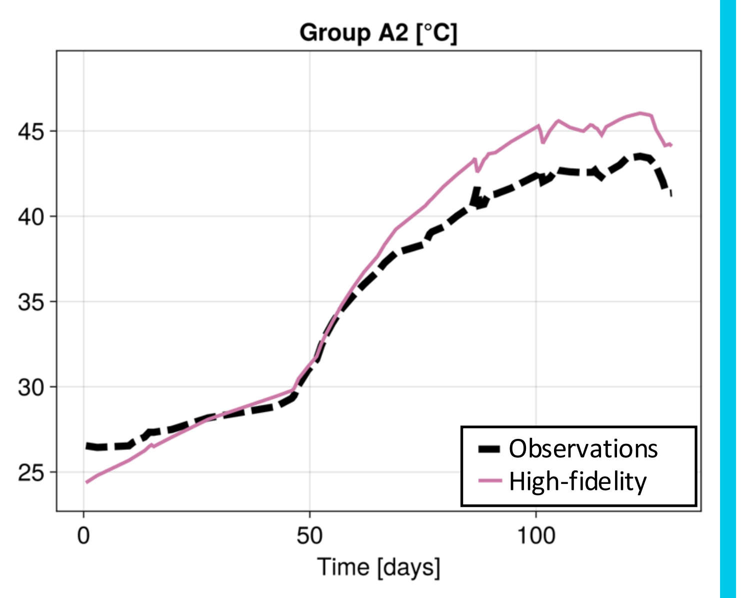
## Wesselkvartalet

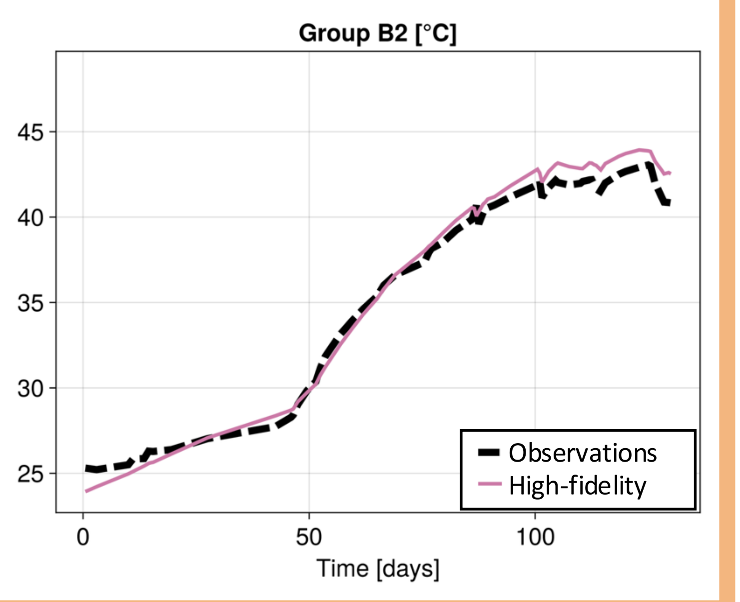
Mixed commercial/residential building in Asker, Norway

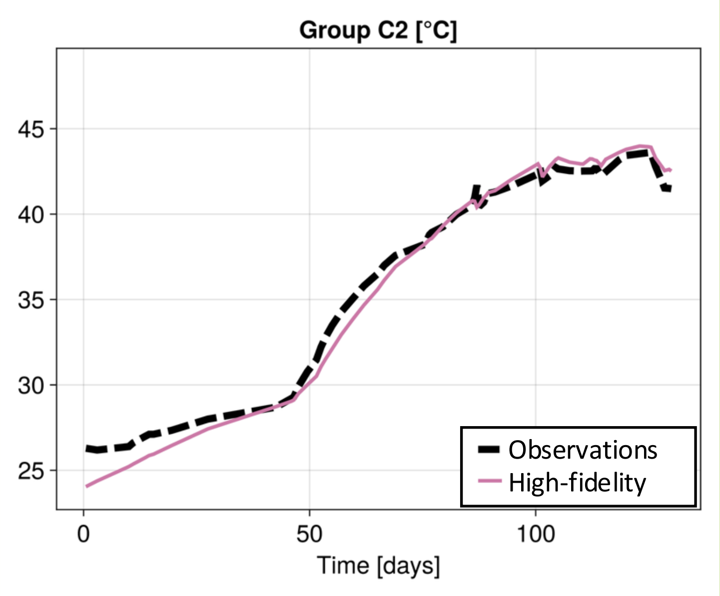
*GOAL: Build a digital twin and simulate using at two resolutions (high-fidelity and proxy); calibrate proxy to observed data*

https://www.wesselkvartalet.no/

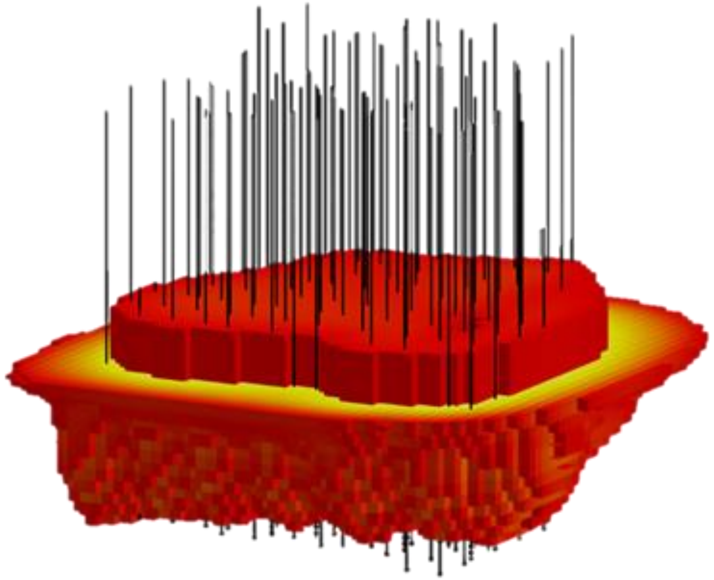


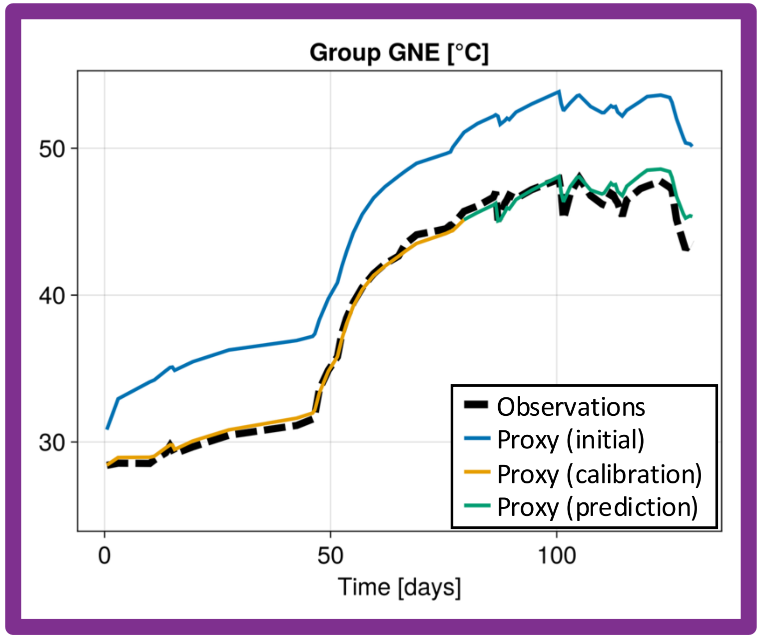

# HIGH-FIDELITY MODEL

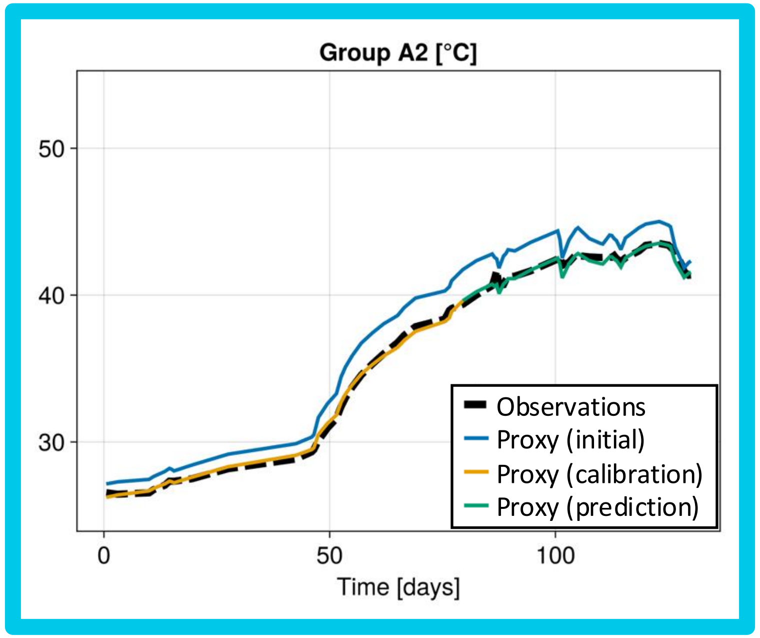


| | | |
|---|---|---|
| # dofs: | 166 153 | Sim. time: 2.57 h |
| # parameters: | 1 433 414 | |

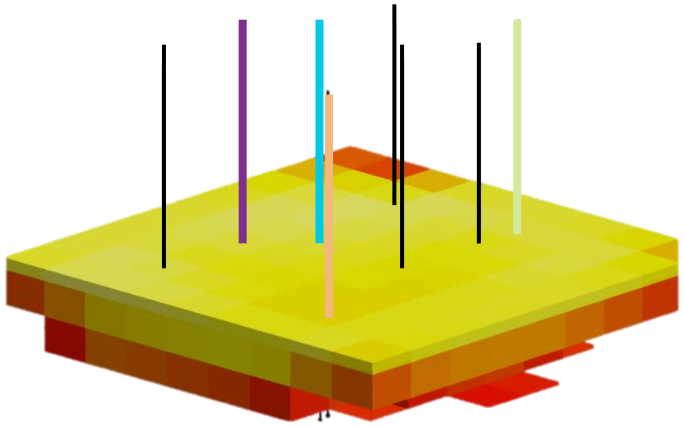
All 97 wells represented
Ten horizontal fractures intersecting all wells

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

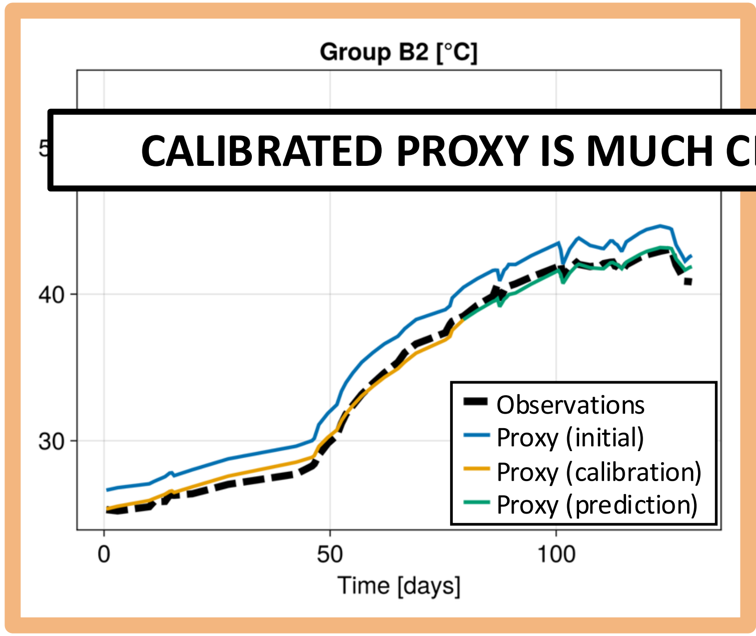


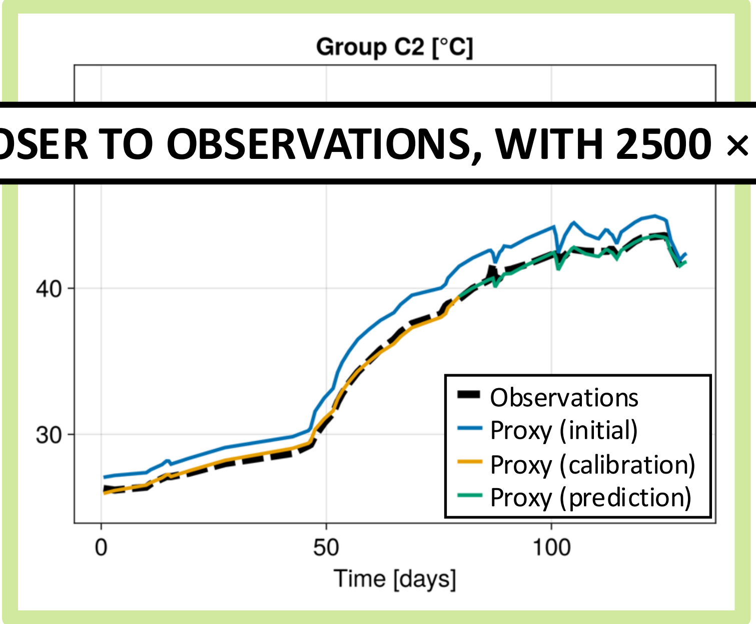




# PROXY MODEL



| | | |
|---|---|---|
| # 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:

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

Reproduces calibration data

Excellent prediction of unseen data

# FJELL SKOLE GEOTERMOS

## BOREHOLE THERMAL ENERGY STORAGE

Under parking lot

100 wells, depth: 50 m, spacing: 4 m

## OPERATION

Heating for school building (10,000 m²)

- Production target: 350 MWh/year
- Low-temperature floor heating: 23–28 °C

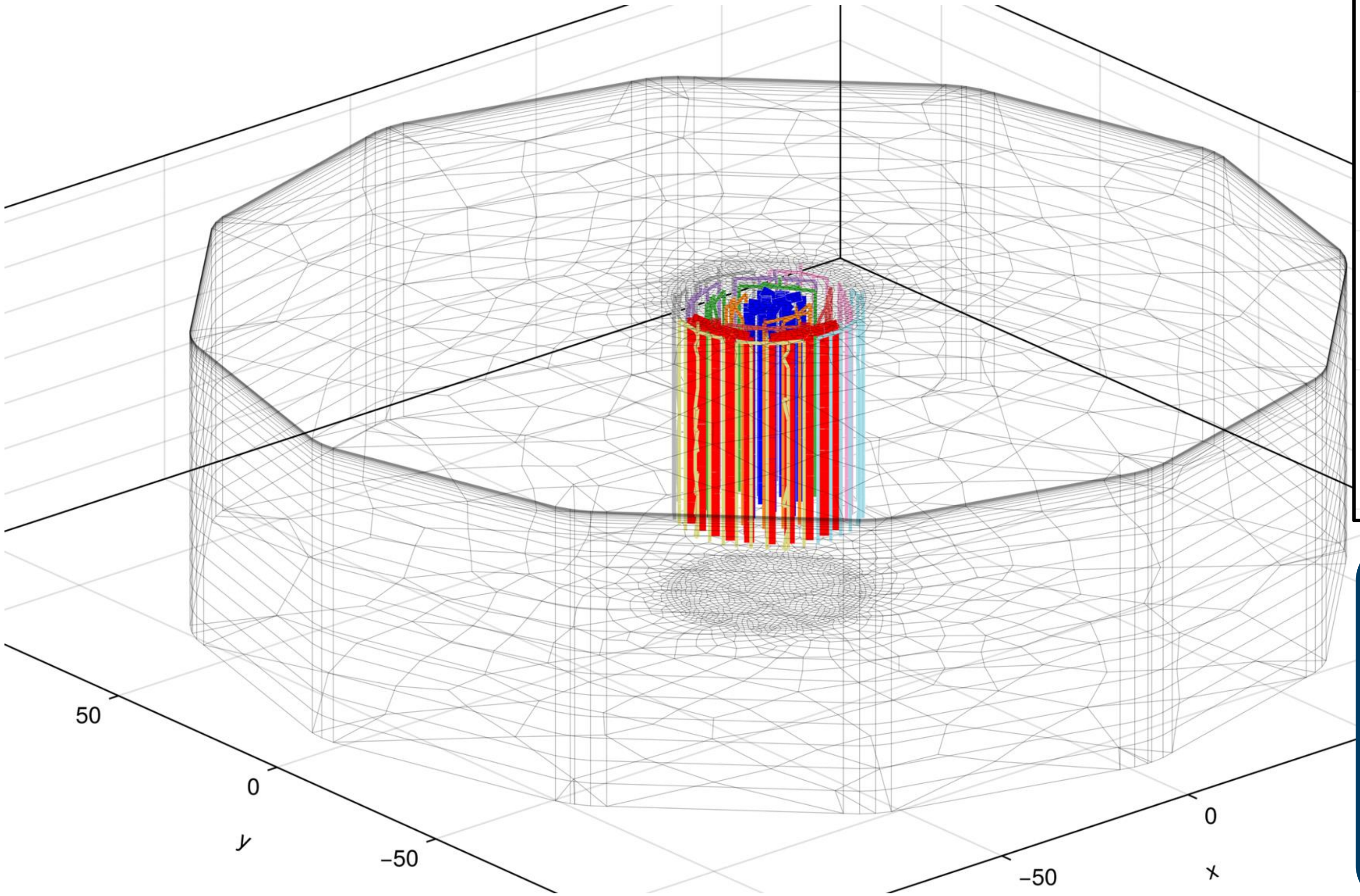

*Goal: Build a digital twin that reproduces observed power and temperature*

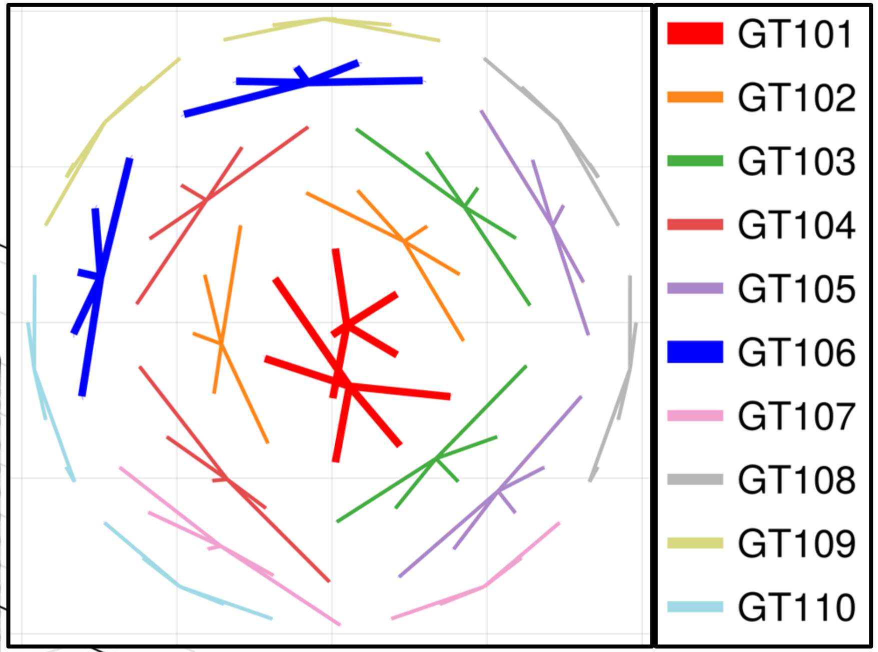
**Fjell elementary school**

Drammen, Norway (Illustration: Drammen Eiendom)

# Fjell GeoTermos digital twin

## Numerical model



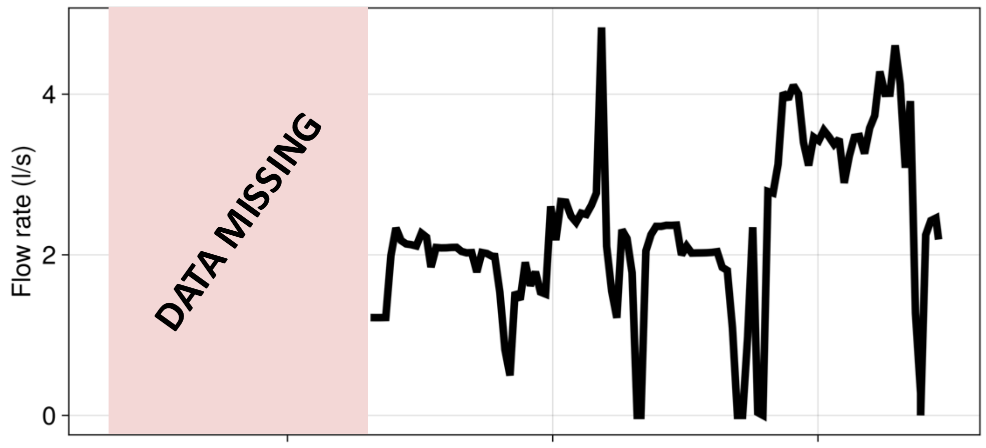



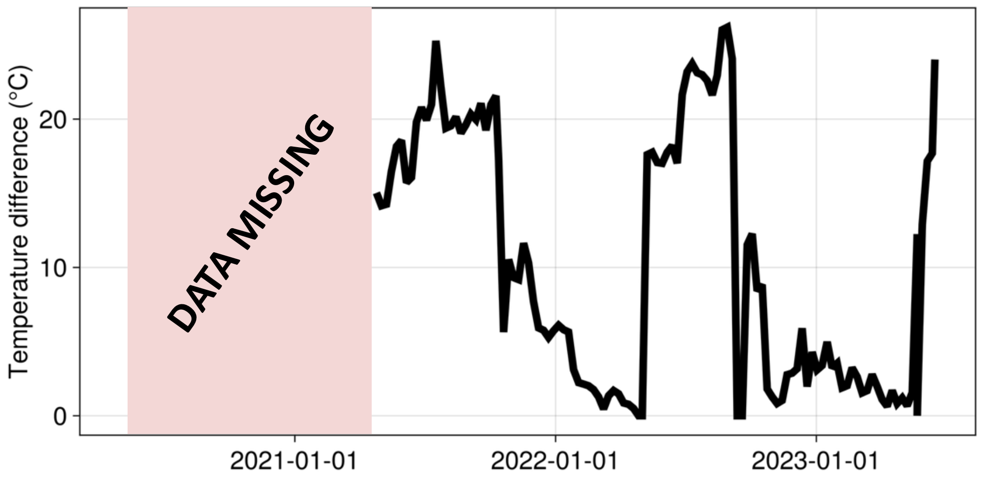

NUMERICAL SIMULATION USING FINITE-VOLUMES

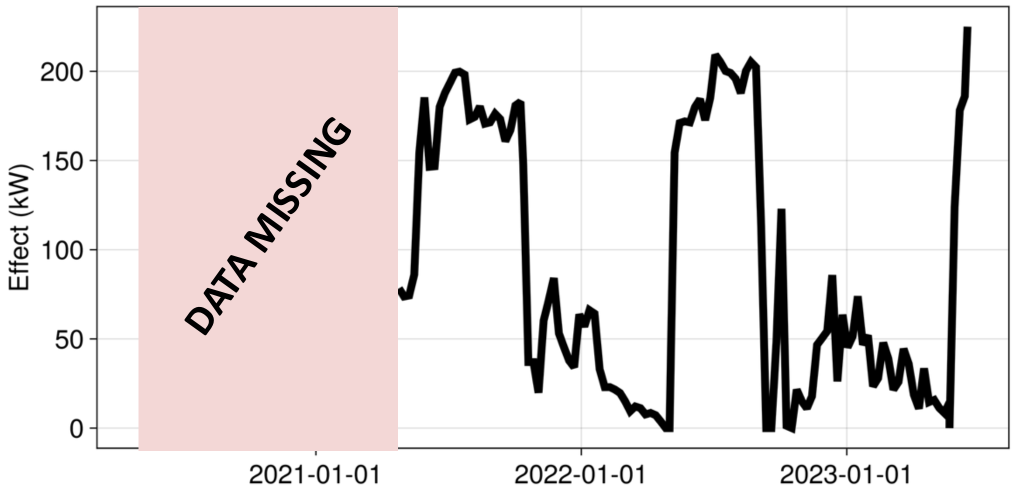
- Governing equations: mass and thermal energy conservation
- Control volumes in space
- Two-point approximation for mass flux (Darcy's law) and heat flux (Fourier's law)
- Single-point ipwind weighting
- Implicit backward Euler in time
  Robust and stable across wide range of parameters/time steps

# Fjell GeoTermos digital twin

## Data from Physical System



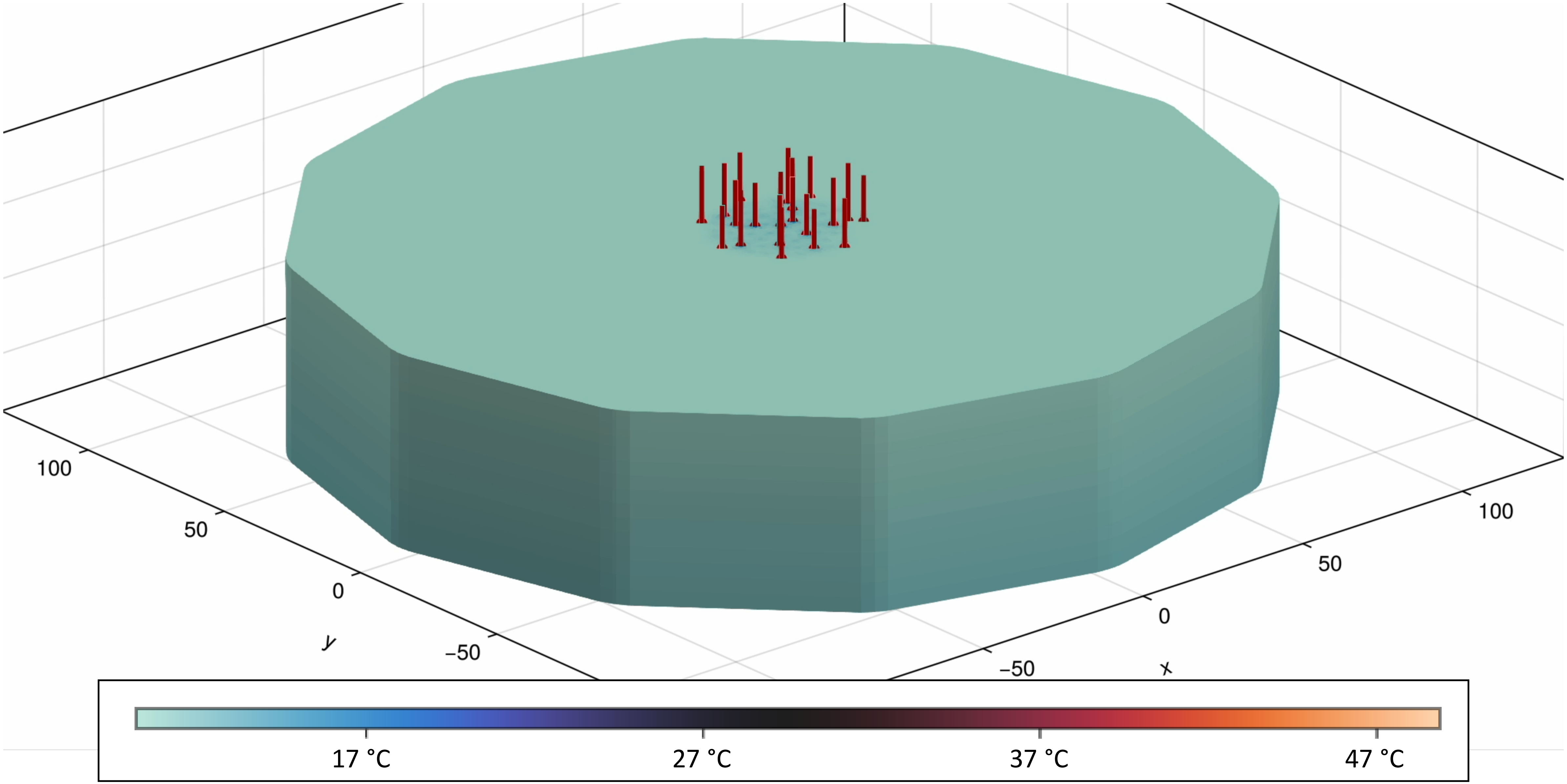




*To simulate the behavior of the GeoTermos, we need flow rates ($r$), injection temperatures ($T_{\text{in}}$), and information about which wells have been active.*

We have time series for flow rates and power

- Missing data for first charging (April–Sept 2020) ☹
- Missing information on active wells ☹
- Missing injection temperatures $T_{in}$ ☹

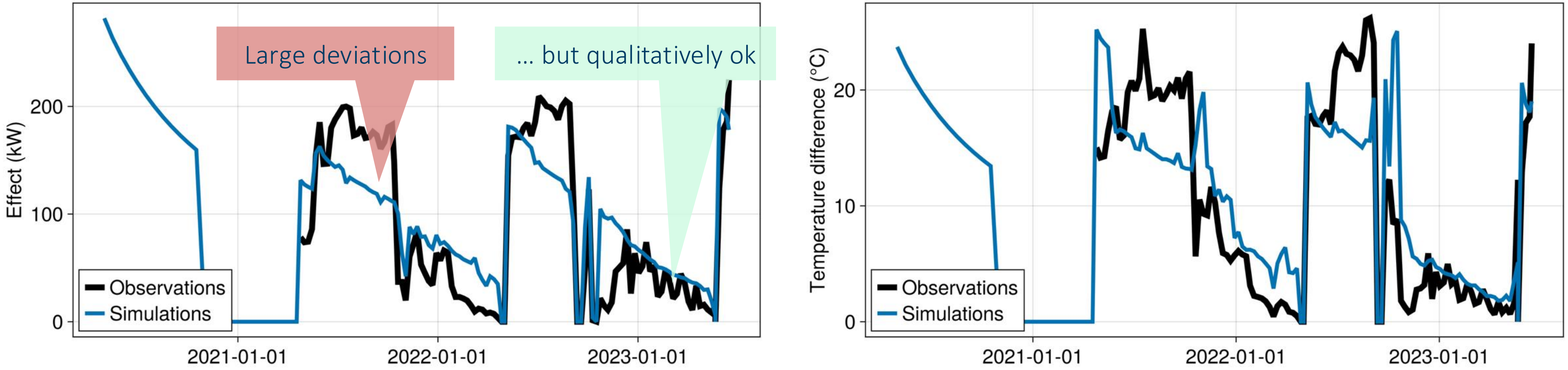
… But can *estimate* $\Delta T = T_{in} - T_{ut}$ from $q = r\rho C_p \Delta T$ ☺



100
50
0
y
-50
100
50
0
-50
x
17 °C
27 °C
37 °C
47 °C

# Fjell GeoTermos digital twin

## Comparison and model calibration




*Main sources of error: missing injection temperatures and missing information about active wells*

# Fjell GeoTermos digital twin

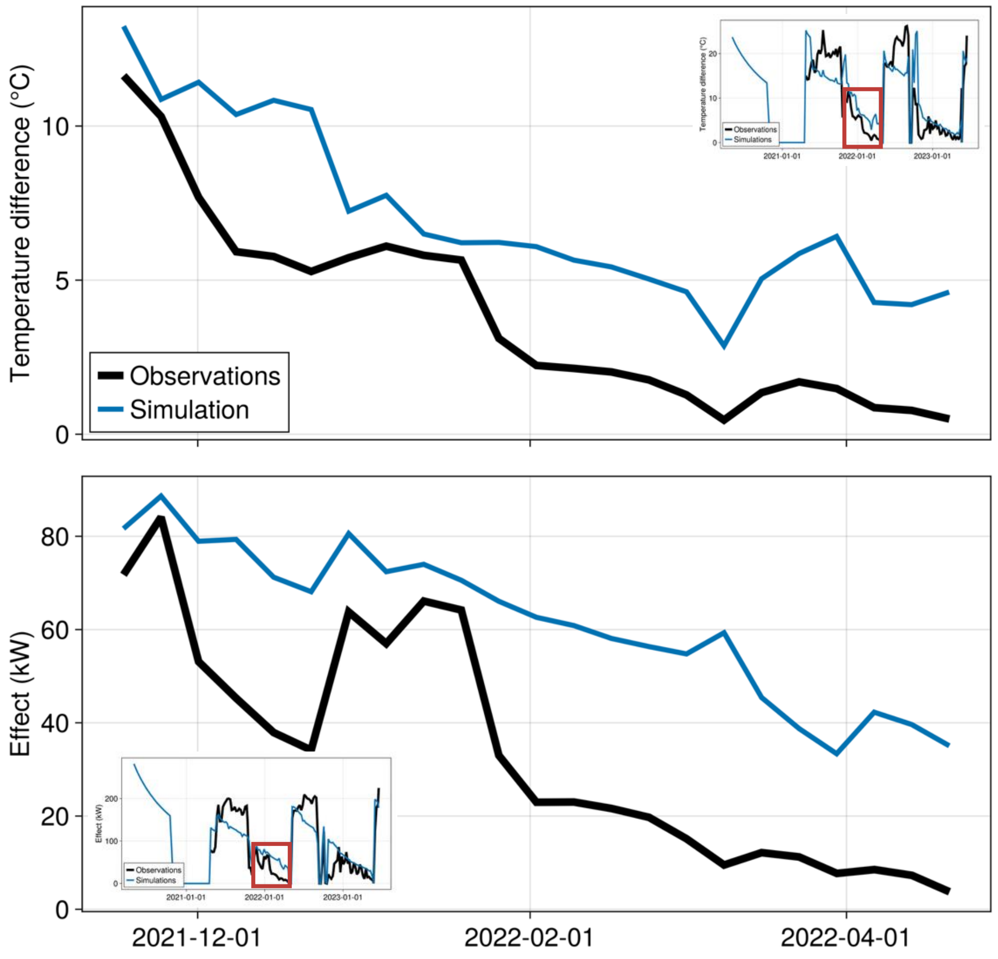
## Comparison and model calibration

### Model calibration

Calibration of thermal conductivity $\lambda$

- In rock and water
- Between well casing and rock
- Calibrated per control volume

OBJECTIVE: $\min_{\lambda} \sum_n [\Delta T_n^{obs} - \Delta T_n^{sim}(\lambda)]^2$



# Fjell GeoTermos digital twin

## Comparison and model calibration

### Model calibration

Calibration of thermal conductivity $\lambda$

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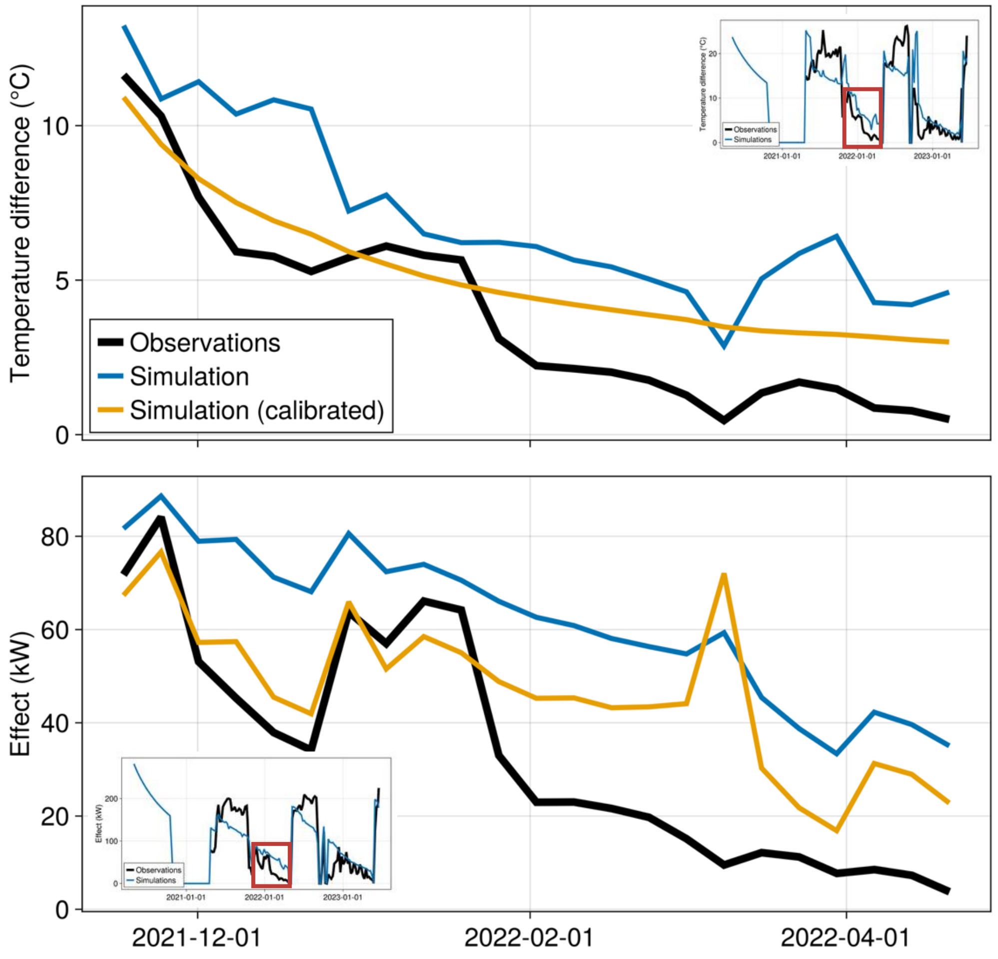
OBJECTIVE: $\min_{\lambda} \sum_n [\Delta T_n^{obs} - \Delta T_n^{sim}(\lambda)]^2$

*Calibration of thermal conductivity improves fit, but more data is needed to better accuracy*

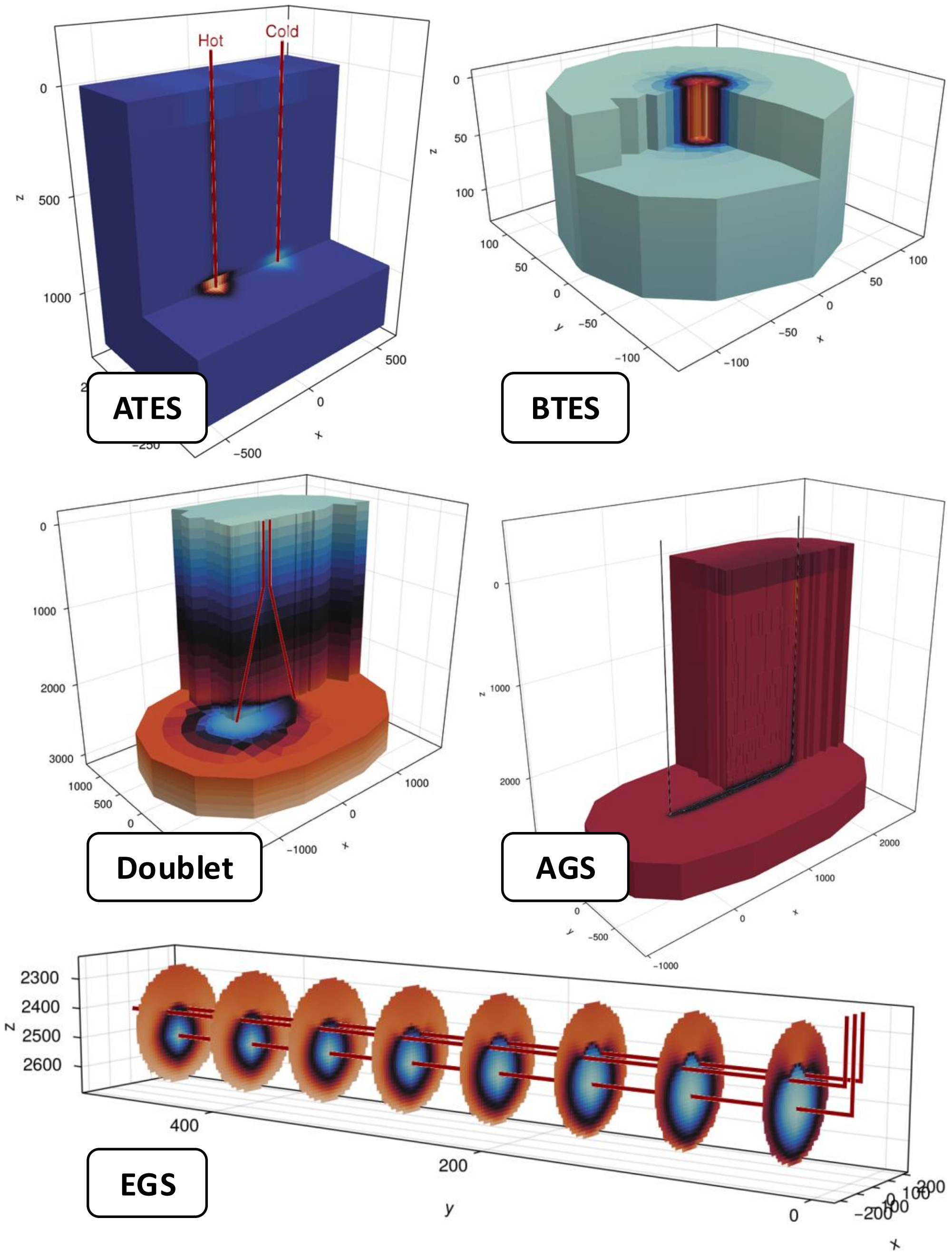


# Fimbul.jl

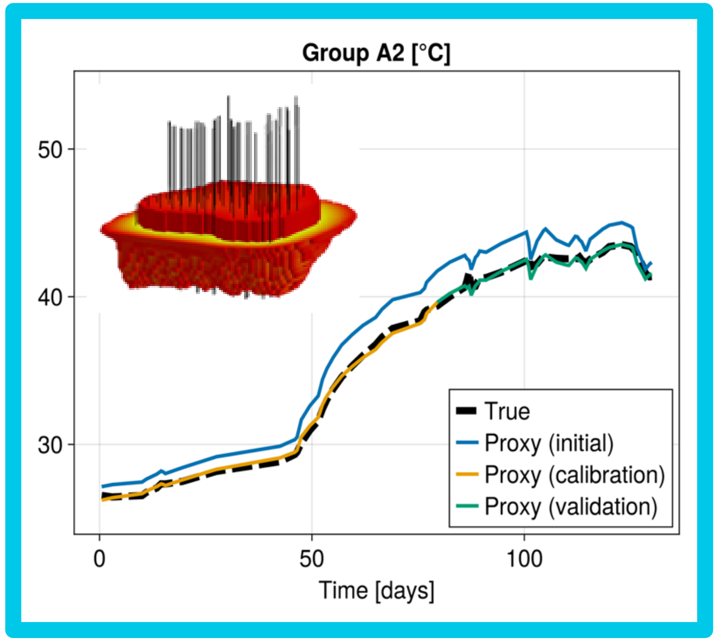
## Fast, flexible, robust, and differentiable geothermal energy simulation in Julia

- Functionality for common geothermal energy applications
  - ATES, BTES, Doublet, AGS, EGS
- Tailored analysis and visualization tools
- Fully differentiable using automatic differentiation
  - **Machine-learning ready simulator!**
- Open-source under MIT license
  - Modification, and distribution with attribution

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



# Summary and Next Steps




## First steps towards digital twinning of UTES

- Enabled by fast, flexible robust, and **differentiable** simulator
- Able to reproduce observed behavior through calibration
- Built with generic functionality
  - Can be used simulate other geothermal energy applications

## Next steps

- Predict future behavior under different strategies
  - Example: predict produced power for a planned charging/discharging schedule
- Prescribe optimal controls (control optimization)
  - Example: optimal charging/discharging given expected heat supply/demand
- Investigate what calibrated parameters reveal about the physical system
  - Example: is the digital twin's thermal conductivity the true conductivity in the physical model?

# Fimbul.jl

Documentation

Abstract

We gratefully acknowledge the **partners of GHOST-DigiT** and the **Research Council of Norway** for funding this research

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strene

Technology for a better society