Derisking geothermal energy by digitalization

A framework for modelling and optimization of underground thermal energy storage systems

Øystein Klemetsdal, Odd Andersen, Stein Krogstad, Computational Geosciences, SINTEF Digital

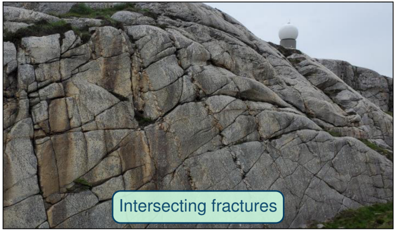
Geoenergy 2023, June 5 2023, Bergen, Norway

Presentation outline

Introduction
The MATLAB Reservoir Simulation Toolbox
Case study: Wesselkvartalet
Case study: Five-spot pattern
Concluding remarks

Shallow geothermal energy storage

- Shallow geothermal reservoirs are excellent candidates for energy storage
  - Constant discharge of base heat, rapid discharge of heat in periods of high demand
- Recharge by circulating hot water from e.g., waste incineration
- The geological setting is typically highly complex
  - horizons, (clay-filled) faults, and intertwined patterns of natural fractures
  - near-well region often hydraulically fractured to enhance inter-well communication



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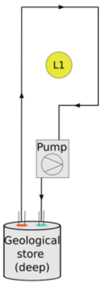
- The geological setting is typically highly complex
  - horizons, (clay-filled) faults, and intertwined patterns of natural fractures
  - near-well region often hydraulically fractured to enhance inter-well communication
- To justify investments and fully utilize potential of shallow geothermal heat storage, **numerical simulation and optimization** is imperative.

RCN IPN with Ruden AS: Development of digital framework for practical modelling of geothermal energy systems, including fractured, geological reservoirs, heat sources, heat pumps, heat exchangers, and end users

Geothermal energy system



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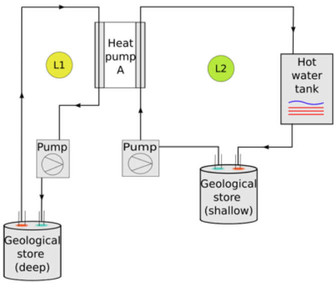

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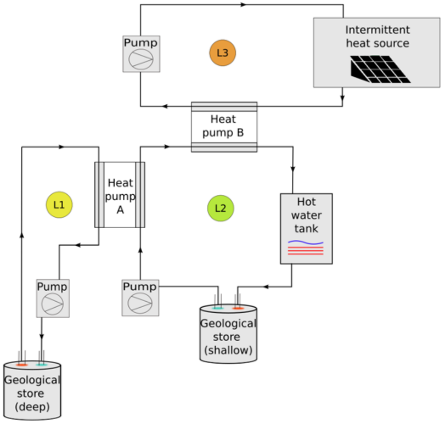

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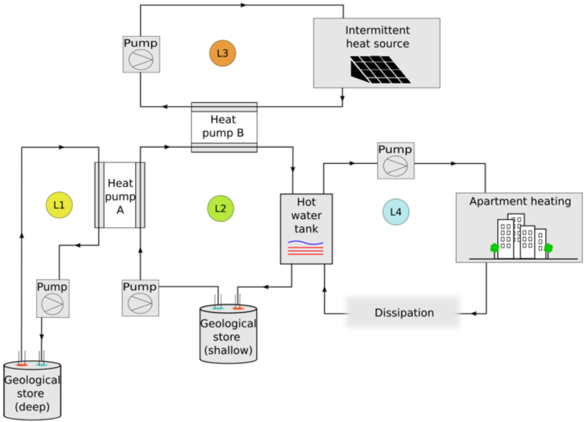

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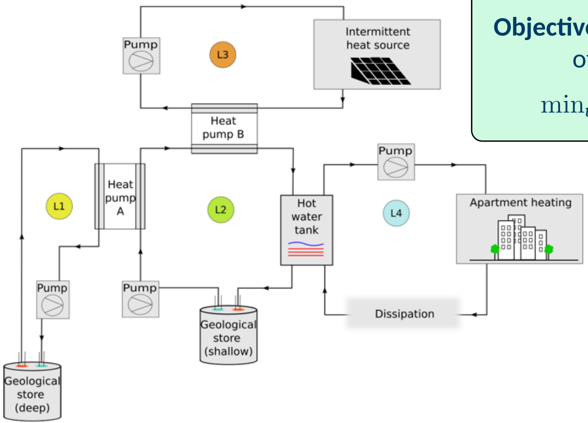
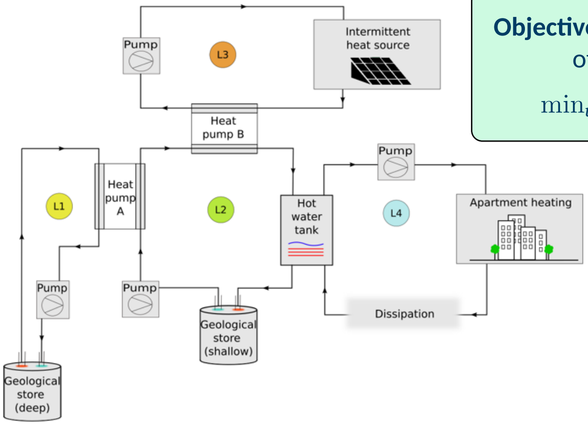


Objective: Minimize cost C of delivering $\overline{P}$ W of heat to apartment complex

$$\min_u C(u;\theta) \quad \text{such that} \quad P(u;\theta) = \overline{P}$$

Geothermal energy system



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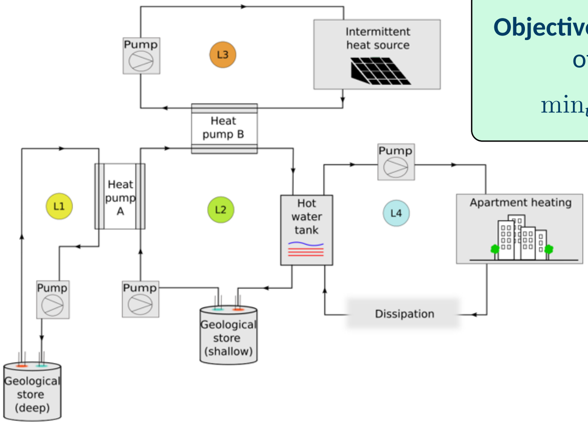

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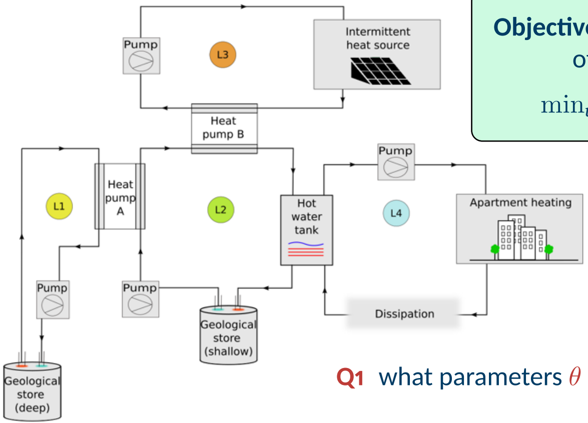

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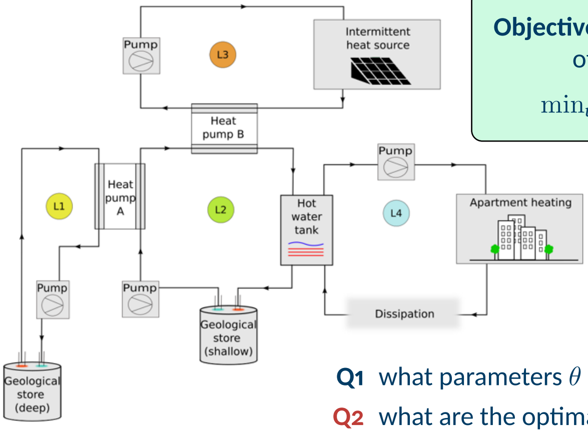

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Controls (rates, temperatures, ...)

Q1 what parameters θ give output that matches observed data?

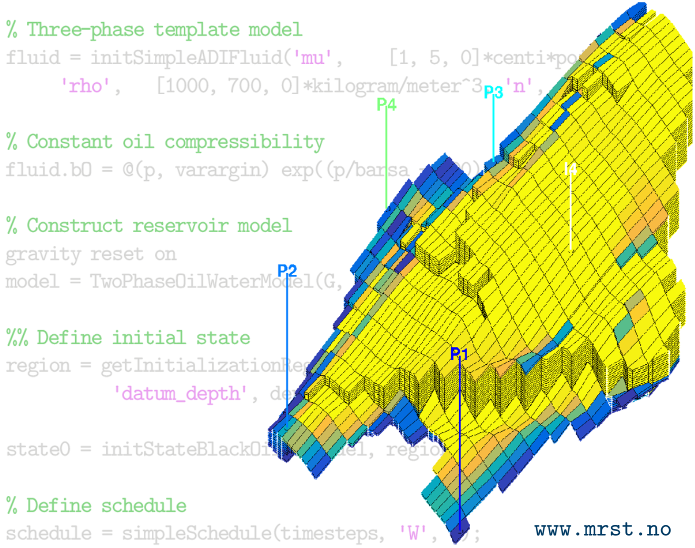
Q2 what are the optimal controls u that minimize cost?

MATLAB Reservoir Simulation Toolbox (MRST)

Transforming research on reservoir modelling

Unique prototyping platform:

- Standard data formats
- Data structures/library routines
- Fully unstructured grids
- Rapid prototyping:
  - Differentiation operators
  - Automatic differentiation
  - Object-oriented framework
  - State functions
- Industry-standard simulation



www.mrst.no

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Differentiation operators

Write discrete equations on form very close to continuous equations

$\nabla \cdot \vec{H}$ $\qquad \vec{H} = -(\lambda_f + \lambda_r)\nabla T$

```
div(H)      H = -(lambdaF + lambdaR).*grad(T)
```

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Automatic differentiation

Combine chain rule and elementary differentiation rules by means of operator overloading to analytically evaluate all derivatives

$\rightarrow$ *Computing Jacobians amounts to writing down residual equations.*

```
[x,y] = initVariablesADI(1,2); z = 3*exp(-x*y)
```

```
x = ADI Properties:        y = ADI Properties:        z = ADI Properties:
    val: 1                     val: 2                     val: 0.4060
    jac: {[1]  [0]}            jac: {[0]  [1]}            jac: {[-0.8120]  [-0.4060]}
```

$\frac{\partial x}{\partial x}$ $\quad$ $\frac{\partial x}{\partial y}$ $\quad$ $\frac{\partial y}{\partial x}$ $\quad$ $\frac{\partial y}{\partial y}$ $\quad$ $\frac{\partial z}{\partial x}\Big|_{x=1,y=2}$ $\quad$ $\frac{\partial z}{\partial y}\Big|_{x=1,y=2}$

MATLAB Reservoir Simulation Toolbox (MRST)

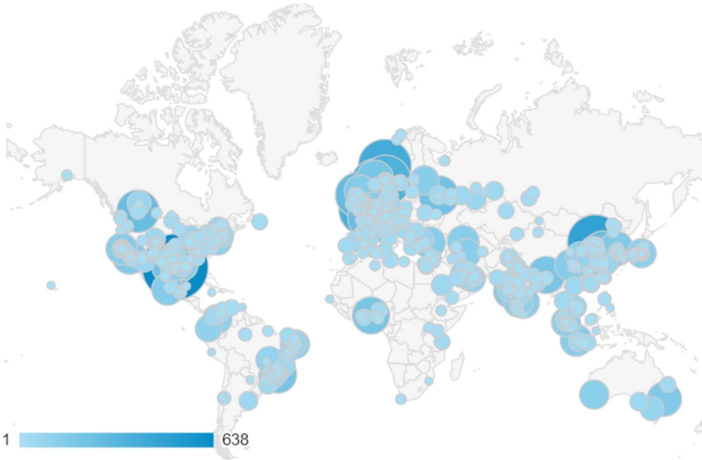
Transforming research on reservoir modelling

Large international user base:

- downloads from the whole world
- 124 master theses
- 56 PhD theses
- 400 journal papers (not by us)
- 144 proceedings papers

Numbers are from Google Scholar notifications

Used both by academia and industry

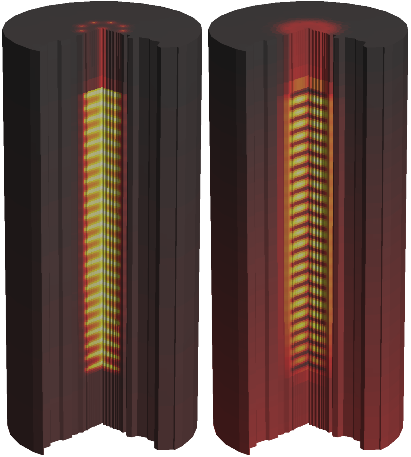


Google Analytics: access pattern for `www.mrst.no`
Period: 1 July 2018 to 31 December 2019
Unique downloads: 5 516 (103 countries and 838 cities)

The geothermal module of MRST

- Low- to medium-enthalpy systems
  - Single-phase, two component H_2O/NaCl
  - Rudimentary support for phase changes
- Applied to applications from shallow, fractured UTES (Ruden) to basin-scale analysis (Uni. Geneva)
- Book chapter (open access)

Collignon, M., Klemetsdal, Ø., & Møyner (2021)

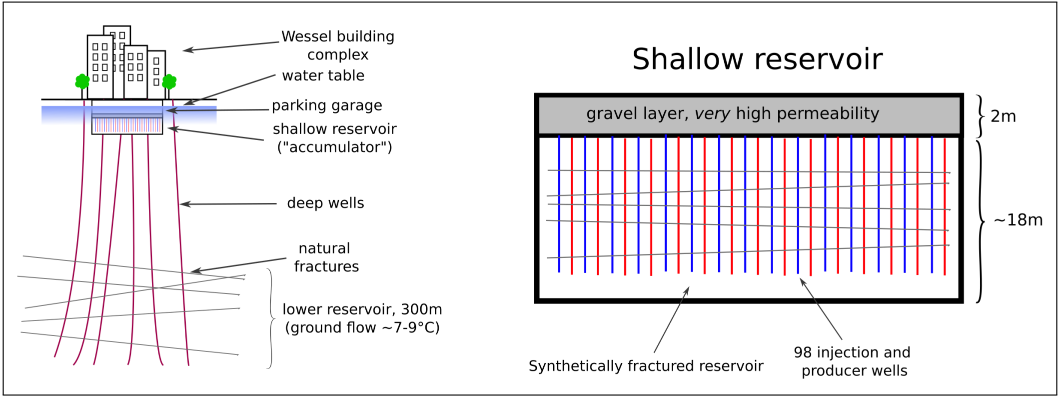


Model tuning: Wesselkvartalet

Wesselkvartalet

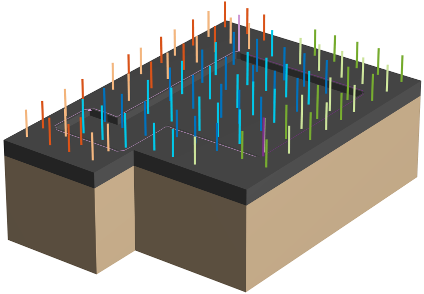
- Newly constructed, mixed residential/commercial building in the city of Asker, Norway
- Integrates a multi-reservoir, shallow geothermal storage facility for heating/cooling
  - Three reservoirs at different depths with very different properties
  - More than 100 wells, coupled in groups
  - Provides constant base load and rapid release of heat at peak loads
  - Heat energy in the winter to distributed deicing system for the city streets

Wesselkvartalet

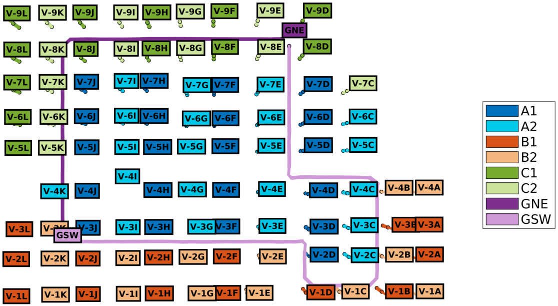


Here: focus on shallow reservoir only

Wesselkvartalet – operation

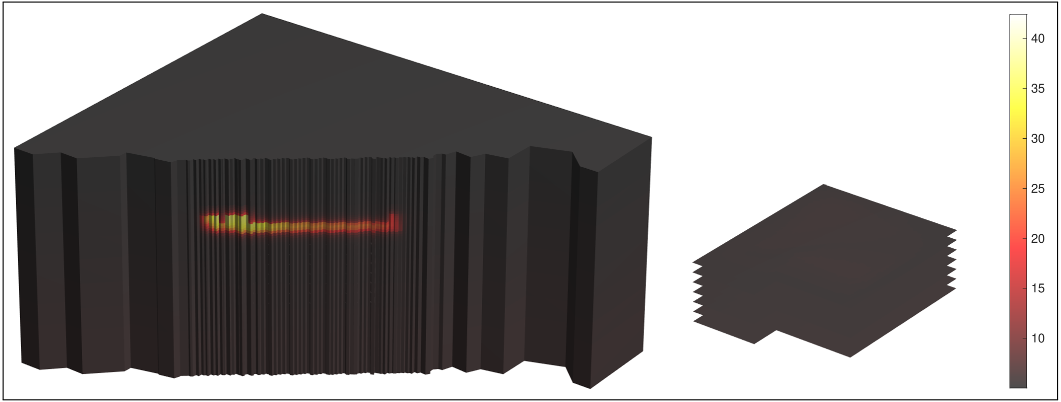


Gravel layer and accumulator



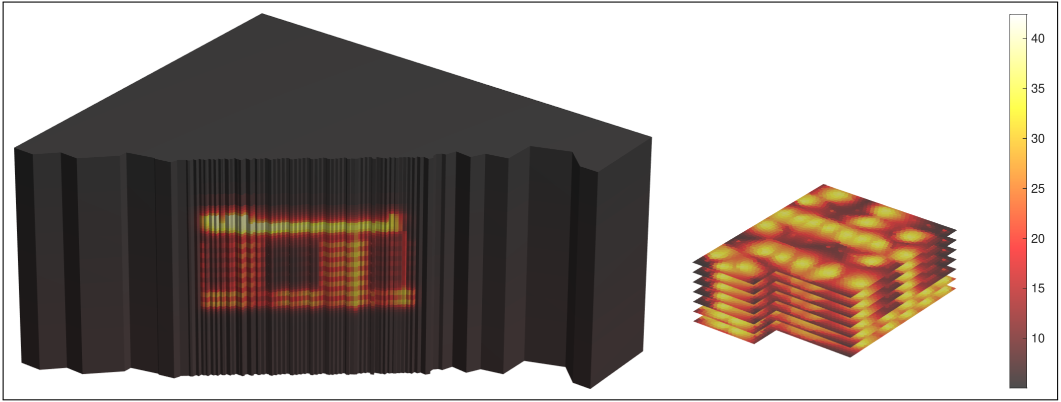
Wells (from above)

Wesselkvartalet – simulation results



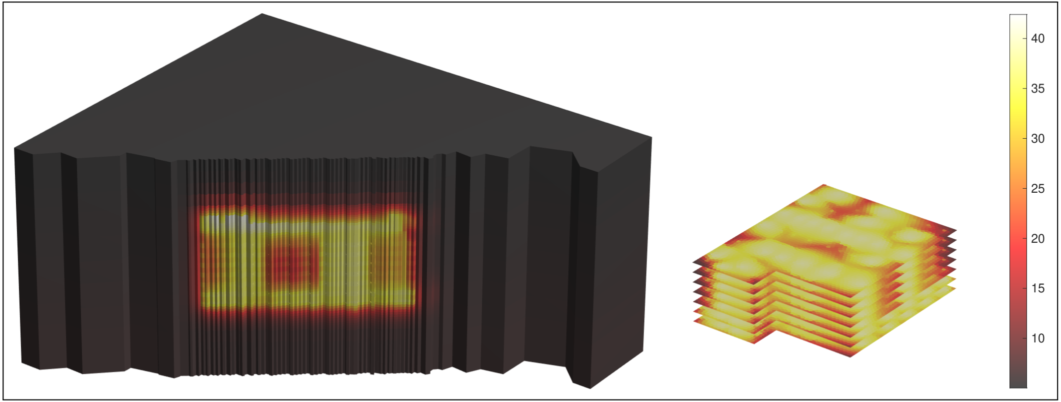
Matrix and fracture temperature (°C), June 28

Wesselkvartalet – simulation results



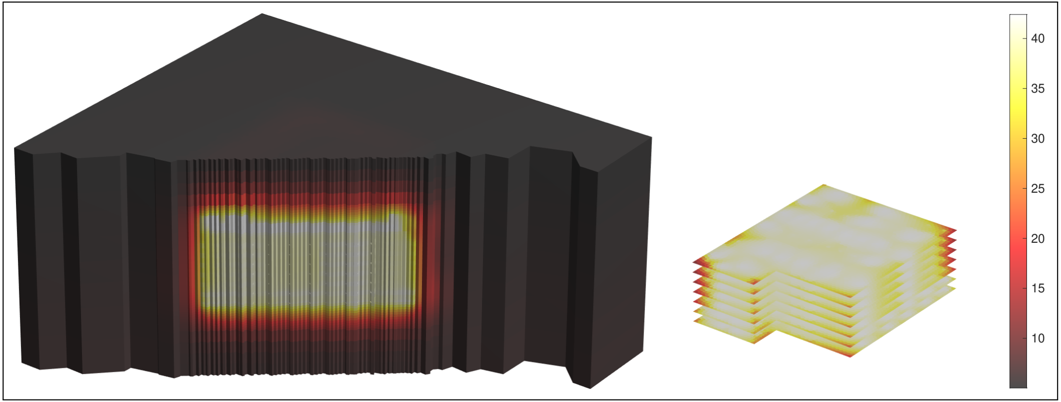
Matrix and fracture temperature (°C), July 22

Wesselkvartalet – simulation results



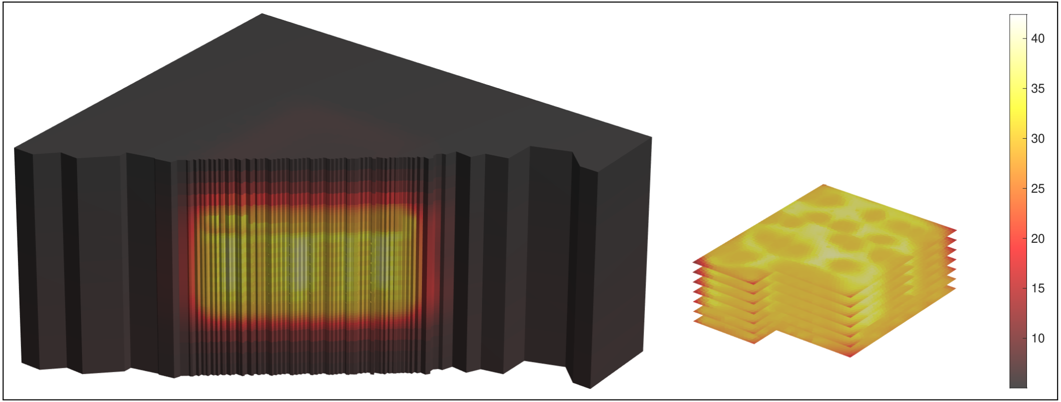
Matrix and fracture temperature (°C), August 28

Wesselkvartalet – simulation results



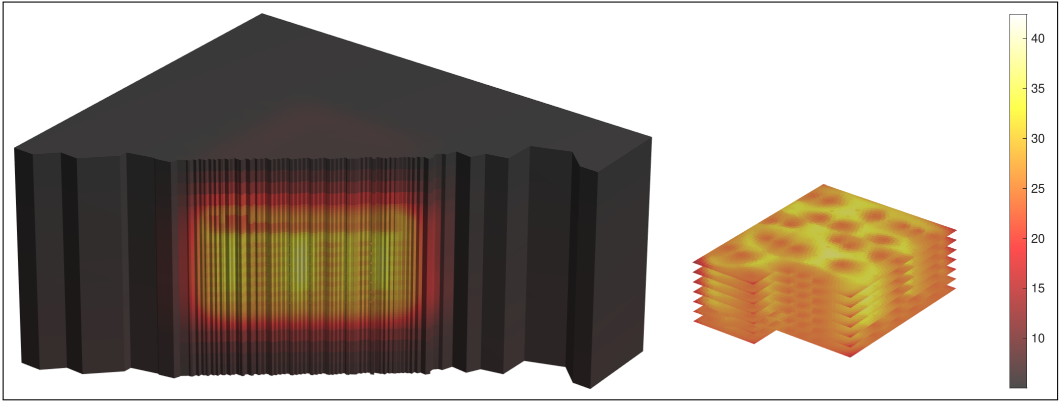
Matrix and fracture temperature (°C), November 21

Wesselkvartalet – simulation results



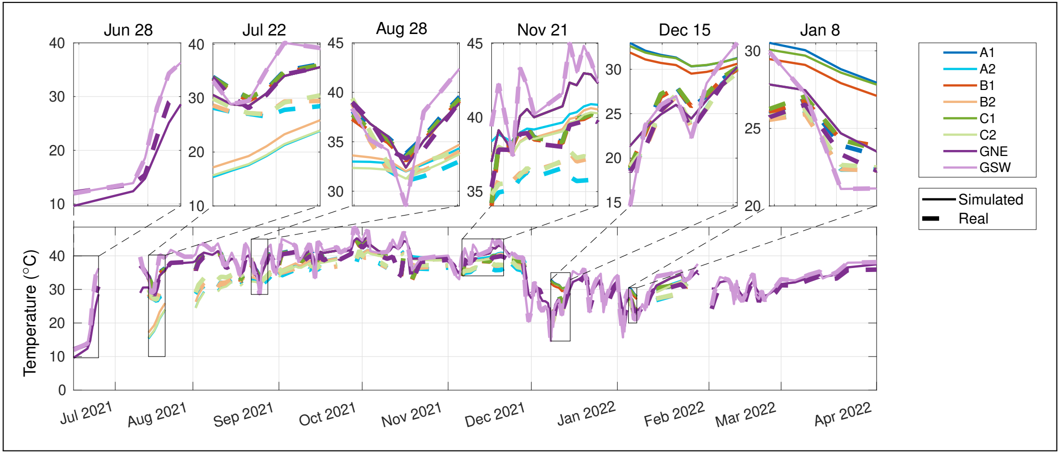
Matrix and fracture temperature (°C), December 15

Wesselkvartalet – simulation results



Matrix and fracture temperature (°C), January 8

Wesselkvartalet – simulation results



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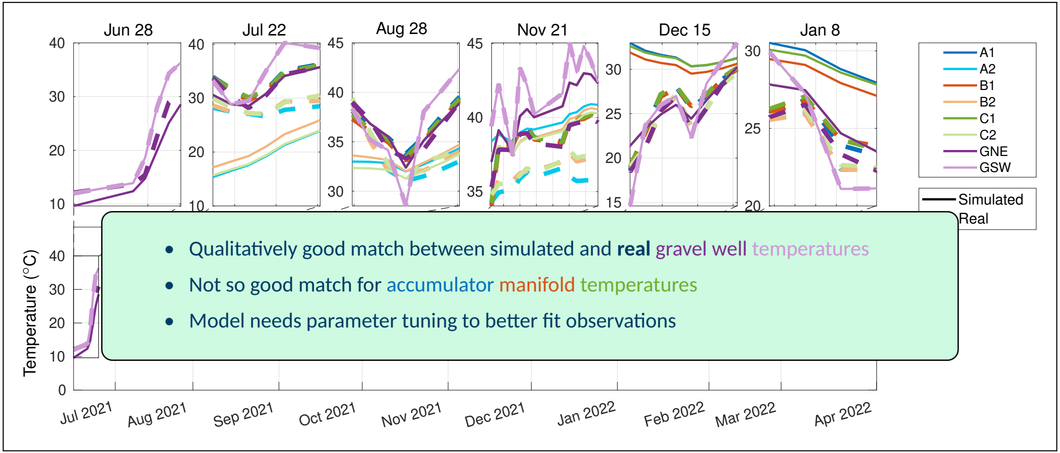
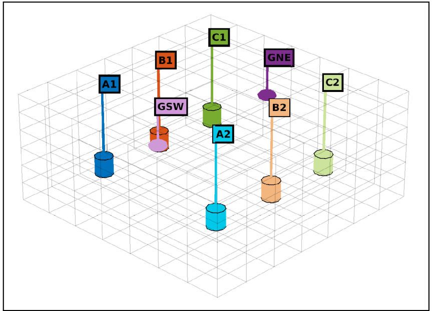


- Qualitatively good match between simulated and **real** gravel well temperatures
- Not so good match for accumulator manifold temperatures
- Model needs parameter tuning to better fit observations

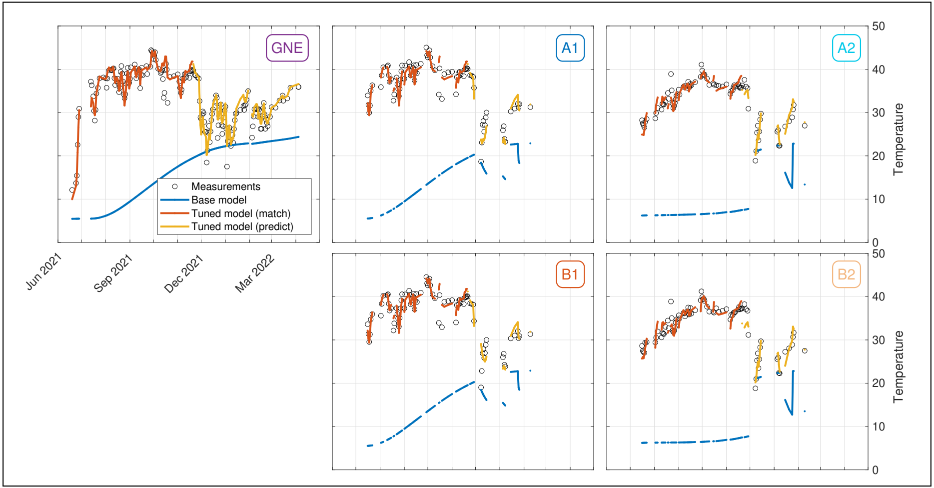
Wesselkvartalet – model tuning



Coarse network model

- Use gradient-based optimization with manifold temperature mismatch as objective
- Tune *coarse-grid network model* with manifolds only (instead of full model w/ 97 wells)
  - CGNet (Lie and Krogstad 2023)
- Parameters tuned: pore volumes, flow/thermal transmissibilities, heat capacities

Wesselkvartalet – model tuning



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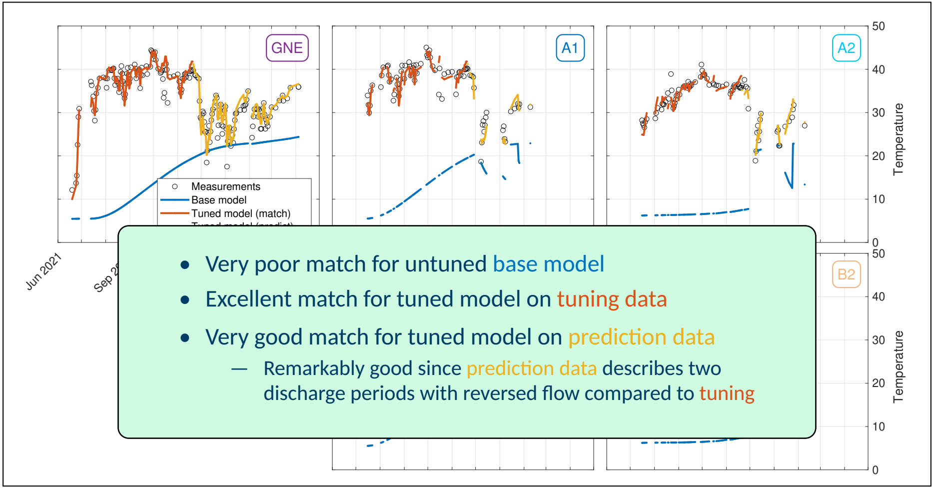

- Very poor match for untuned base model
- Excellent match for tuned model on tuning data
- Very good match for tuned model on prediction data
  - Remarkably good since prediction data describes two discharge periods with reversed flow compared to tuning

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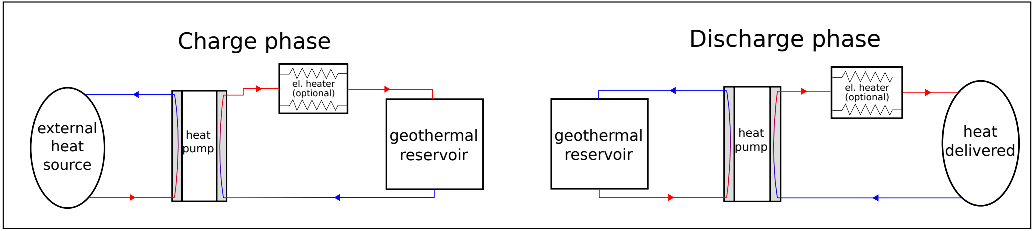
Control optimization: Five-spot pattern

Storage in five-spot pattern

Optimal control

- Setup: heat storage in $60 \times 60 \times 20$ m box, homogeneous perm/poro of 2 md/0.04
- Charge for specific time, then discharge to provide peak load to external application
- Objective: find injection rate/temperature that minimizes associated energy costs



Storage in five-spot pattern

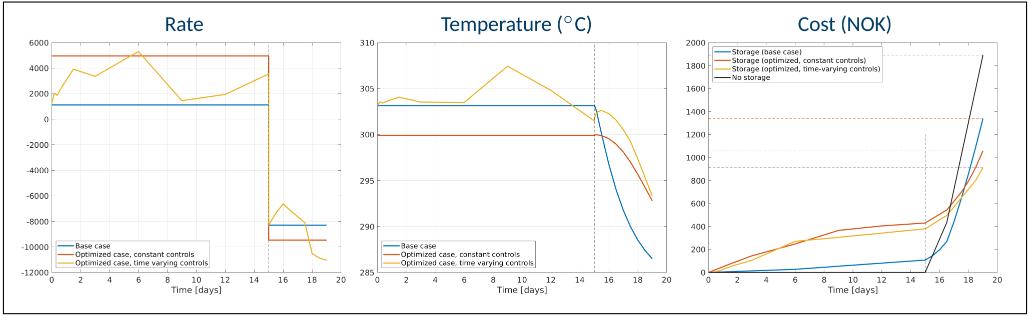
Optimal control – complex scenario

	Complex scenario
Charge period (days)	15
Discharge period (days)	4
Energy price (NOK/kWh)	0.75 - 1.5 - 3.0
Charge: max power from source (MW)	1
Discharge: power delivery required (MW)	8
Initial reservoir temperature, T_0 (°C)	10

Four strategies: no heat storage, base case storage, optimized storage with constant and varying temperature/rate

Storage in five-spot pattern

Optimal control results – complex scenario



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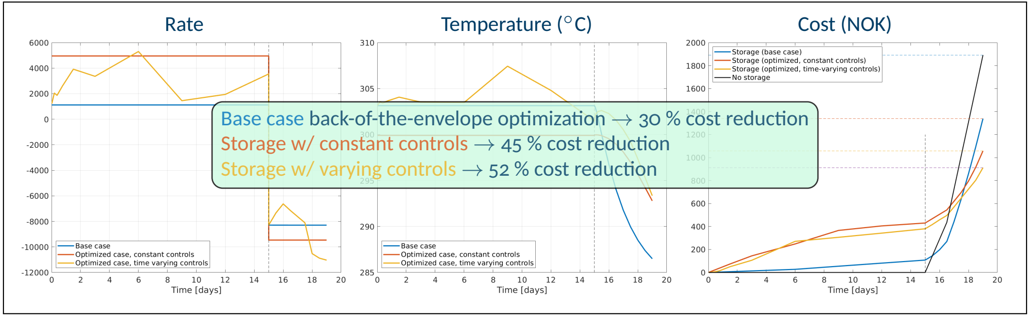
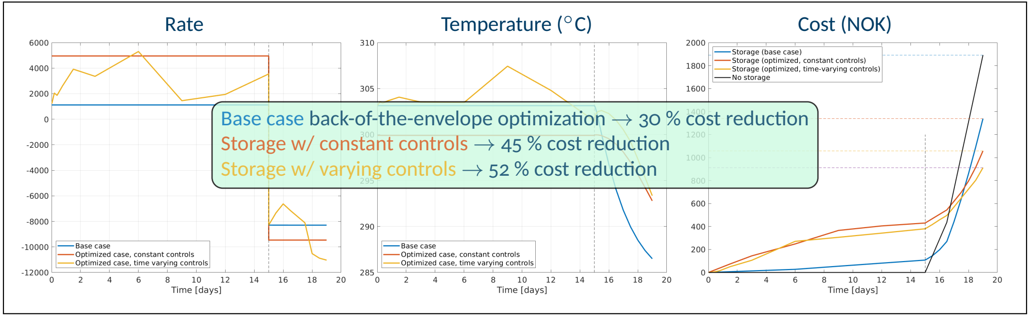


Base case back-of-the-envelope optimization → 30 % cost reduction
Storage w/ constant controls → 45 % cost reduction
Storage w/ varying controls → 52 % cost reduction

Storage in five-spot pattern

Optimal control results – complex scenario



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Storage w/ constant controls → 45 % cost reduction
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*Constantly varying rate/temperature likely not possible – adjusting at given intervals more tractable

Concluding remarks

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Conclusions

- Integrated framework for modelling and optimization of geothermal energy storage systems
  - Based on methods from simulation of oil and gas reservoirs
  - Incorporates key components: reservoirs, heat sources, (heat)pumps, heat exchangers, end users
  - Gradient-based optimization capable of optimal control and parameter tuning
- Applicable to a range of industry-relevant cases

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Concluding remarks

Further work and discussion points

- Identify relevant objective functions for different stages of a project

Stage	Goal	Objective
Planning	Justify investments	Levelized cost of energy
Construction	Find optimal plant configuration	Heat loss
Operations	Find optimal controls	Net present value

  - To what extent is such a framework useful/reliable in the different stages?
- Model parameter tuning has only been tested for very simplified models
  - Open question: can this be used to infer physical properties of the underlying system?

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Concluding remarks

For the interested

- Book chapter on geothermal modelling with MRST (open-access):
  Collignon, M., Klemetsdal, Ø, Møyner, O. (2021)
  Simulation of Geothermal Systems Using MRST
  Cambridge University Press. doi: 10.1017/9781009019781.018

- Conference paper on modelling and optimization of geothermal energy systems:
  Klemetsdal, Ø., Nilsen, H. Krogstad, S., Andersen, O., Bastesen, E. (2022)
  Modeling and Optimization of Shallow Geothermal Heat Storage
  ECMOR 2022, Sep 2022. doi: 10.3997/2214-4609.202244109

- Minisymposium on practical geothermal simulation in SIAM Geosciences:
  Klemetsdal, Ø, Andersen, O.
  MS65: Practical Simulation of Geothermal Energy Systems
  2023 SIAM Conference on Mathematical & Computational Issues in the Geosciences
  Bergen, June 19–22, 2023

Acknowledgements

The authors would like to thank Ruden AS, Wessel Energy AS, and Kvitebjørn Varme AS for allowing the presentation of this work

This research was funded in part by The Research Council of Norway, Grant No. 309651

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