Assessment of Helical Ground Heat Exchangers for Residential Heat Pumps

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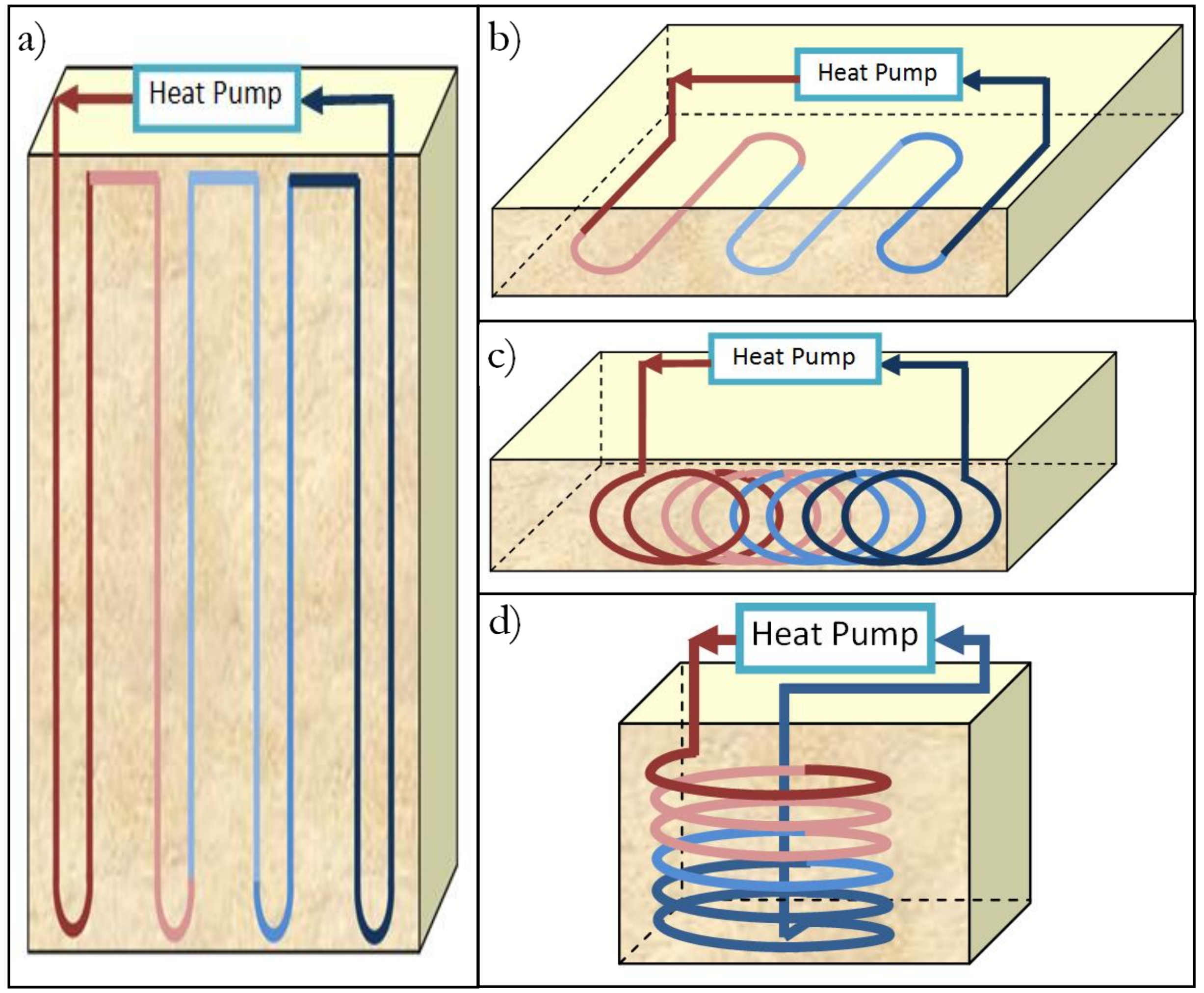
Advisor: Prof. Vinod Narayanan

Ground Heat Exchangers (GHE): Large diameter Shallow Bore Helical design

- GHE: Ground as a sink/source instead of ambient air.



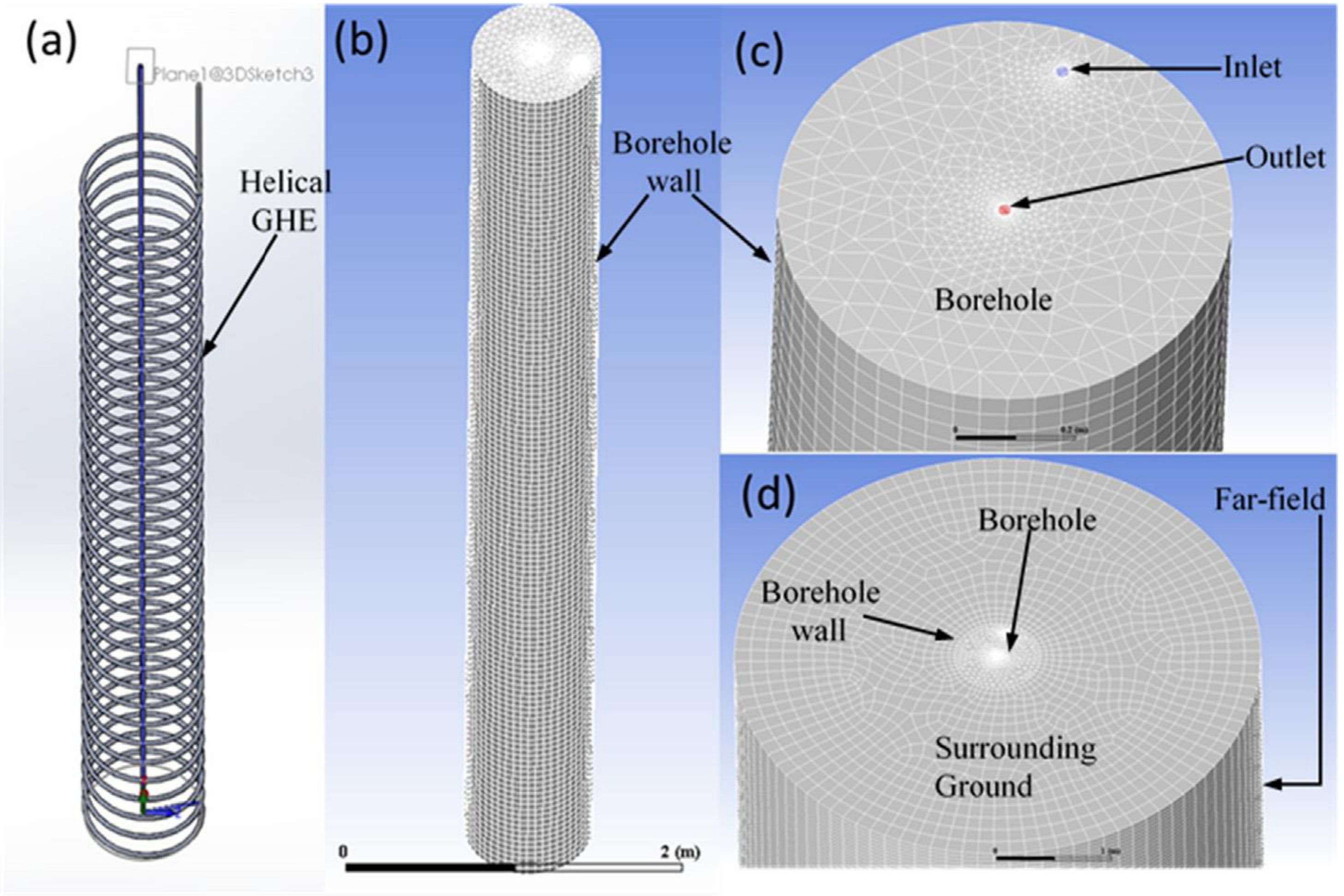
(a) Vertical, (b) Horizontal, (c) Slinky & (d) Helical GHEs.

Parameters	Values
Helix pitch	0.152 m (6 in.)
Helix diameter	0.559 m (22 in.)
GHE spacing	4.572 m (15 ft)
Depth of GHE top	0.914 m (3 ft)
Height of the GHE coil	5.182 m (17 ft)
Pipe diameter	ID 21.34 mm OD 16.94 mm (Nominal ½ in.)
Tube material	HDPE
Backfill	Native soil
Heat-carrier fluid	Water
Supply pipe	Helical pipe

Helical GHE installation photographs and parameters, Honda Smart Home (HSH), Davis CA

Computational Models: CaRM and CFD

- Two models
  - Capacitance and Resistance model (CaRM)
  - Computation fluid dynamics model
- CaRM model
  - Originally developed by Prof. Zarrella
  - Computationally more efficient
- CFD model
  - Highly detailed
  - Computationally intense
  - Provides finer resolution of ground temperatures



Objectives

1. CaRM model improvements	2 slides
2. Impact of moisture	5 slides
3. Parametric study	7 slides
4. Helical GHE response factor	2 slides

Research collaborators

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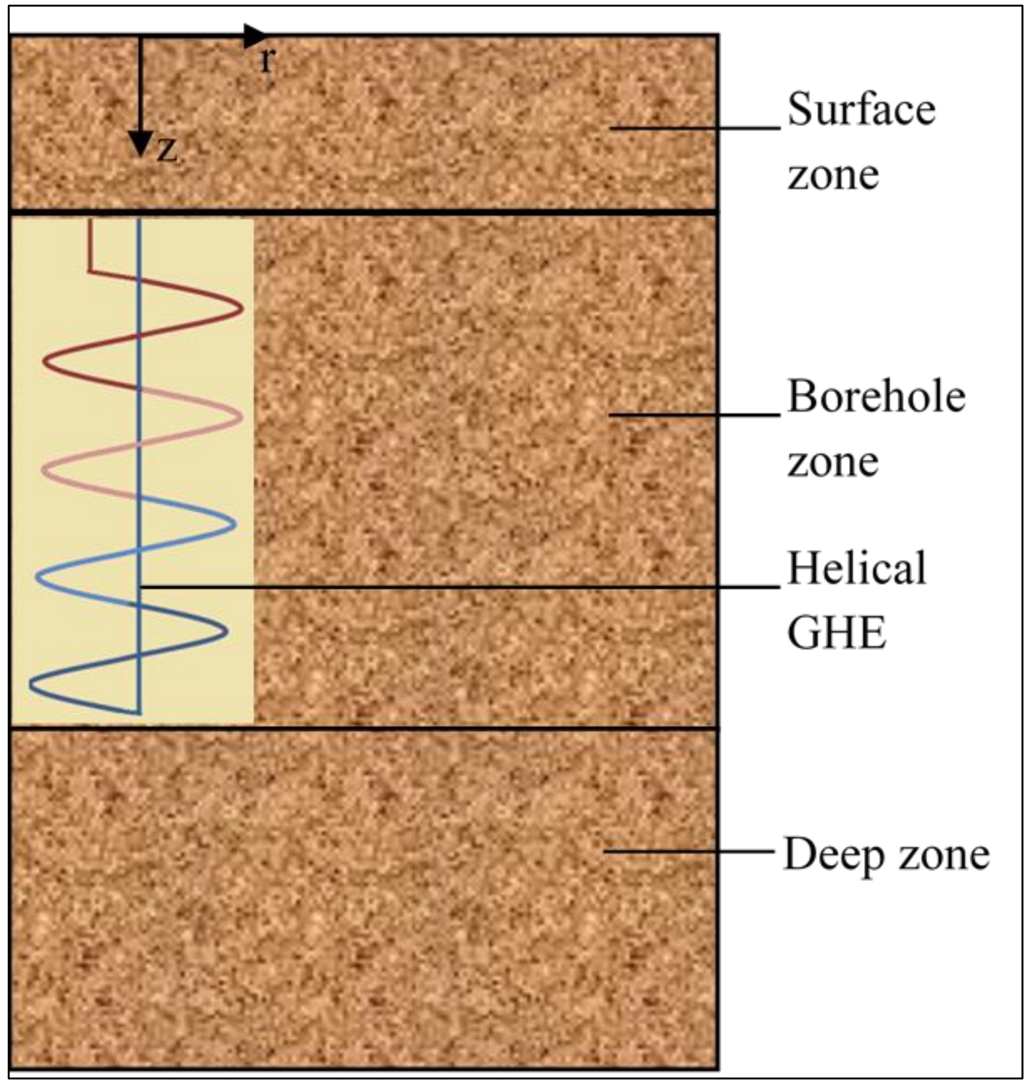
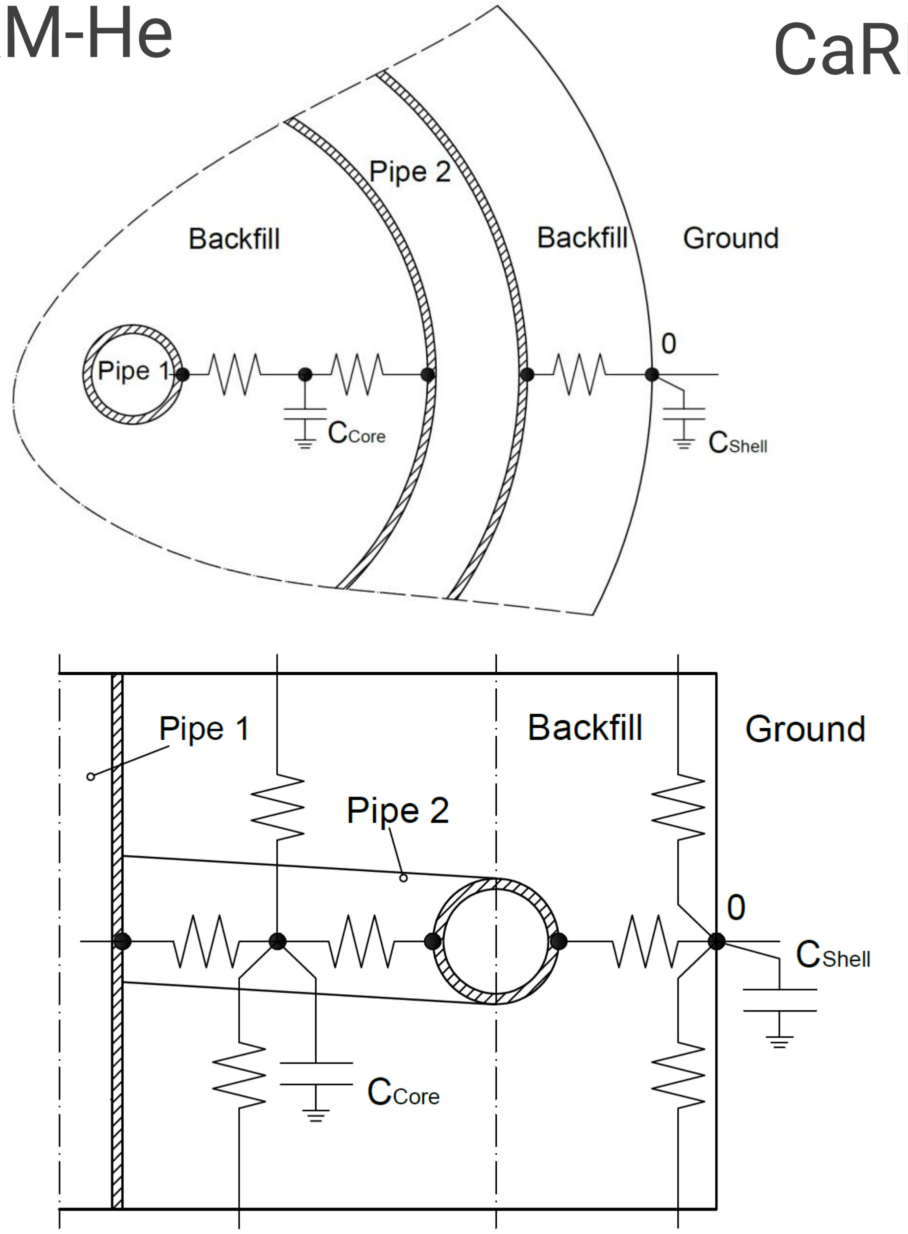
- Prof. Angelo Zarrella, University of Padova, Italy.
- David Springer, Frontier Energy.
- Richard Bourne, Integrated Comforts Inc.
- Curtis Harrington, Western Cooling Efficiency Center.

1) CaRM Model improvements

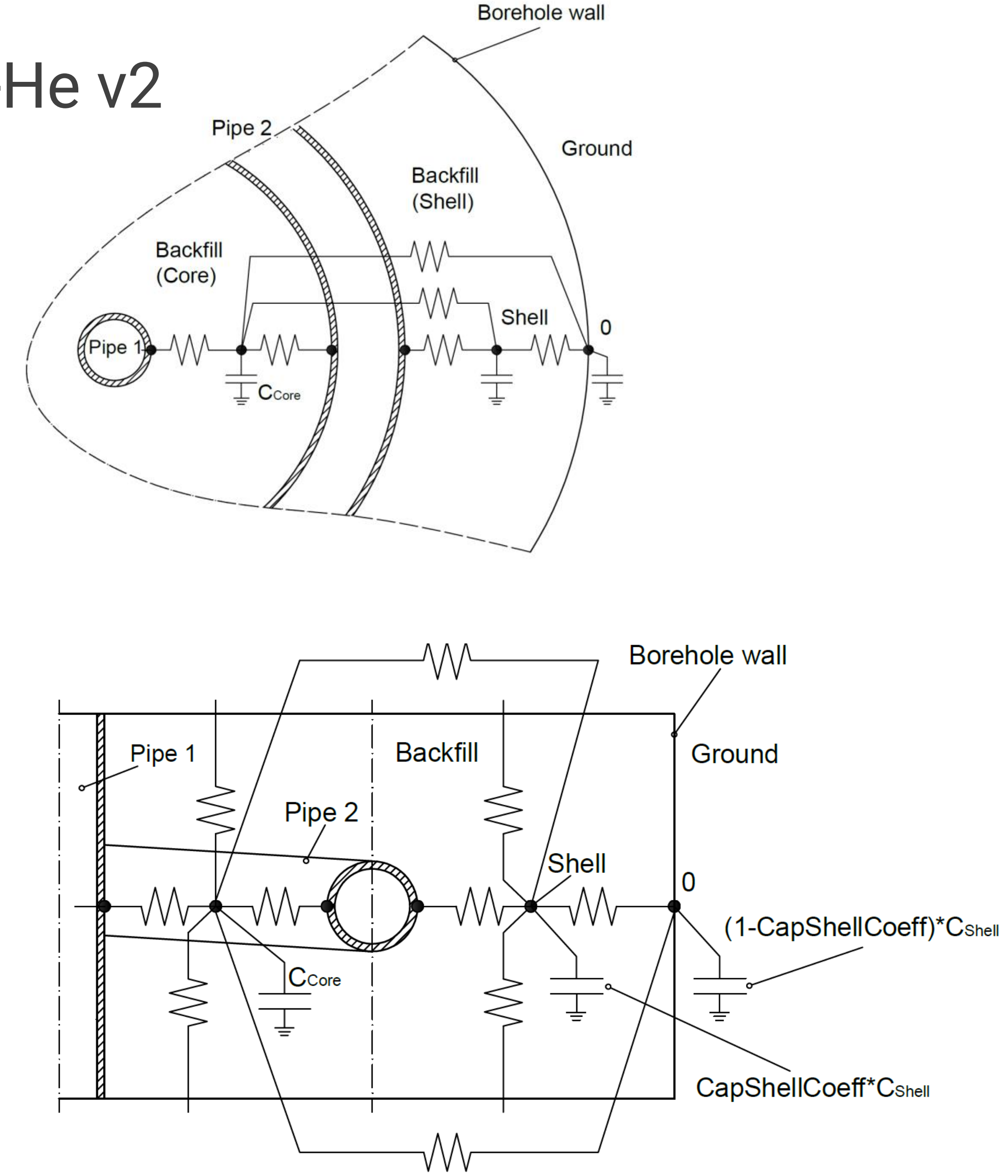
- Improvements using CFD simulation results and site data



CaRM-He

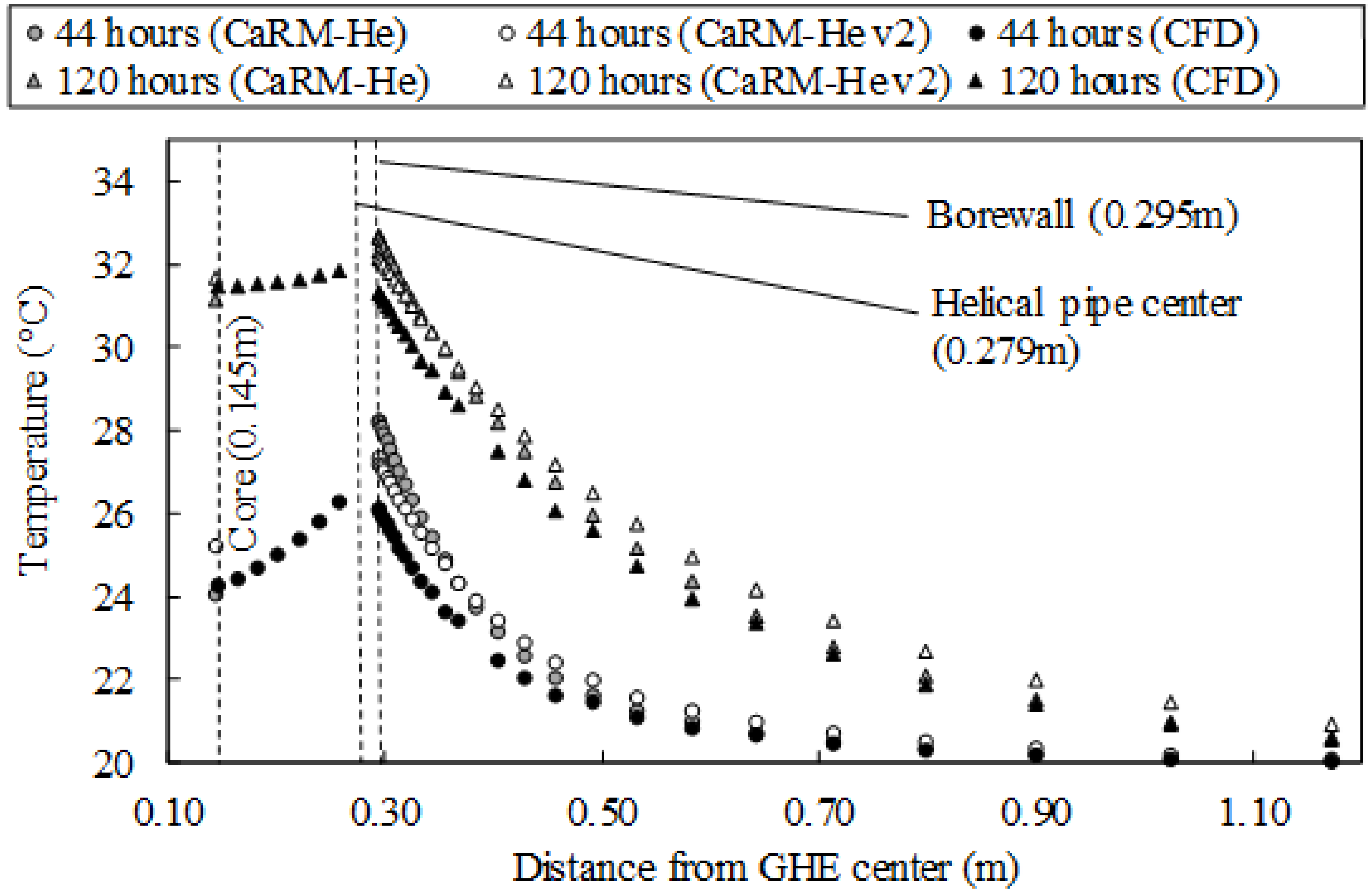


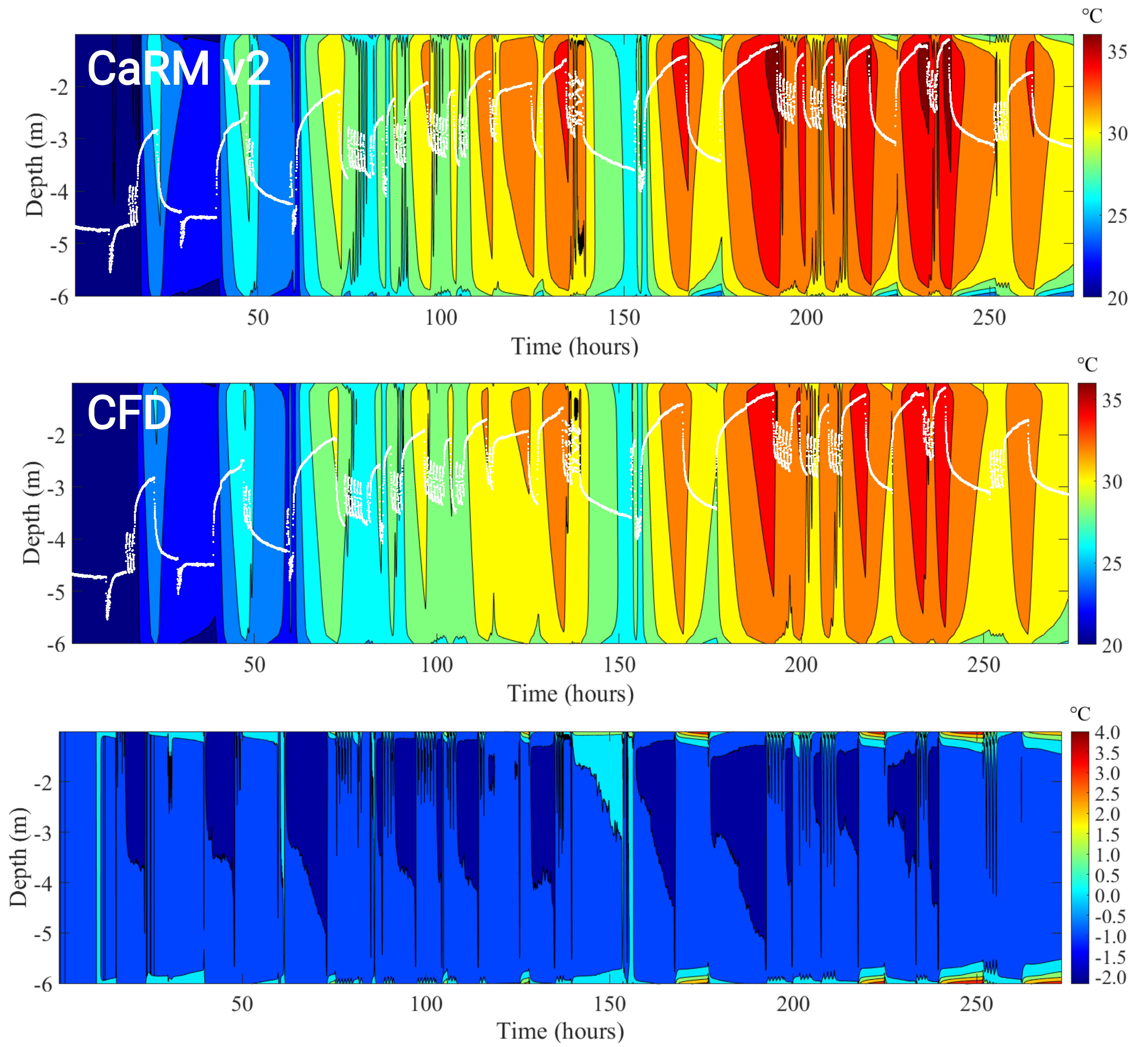
CaRM-He v2



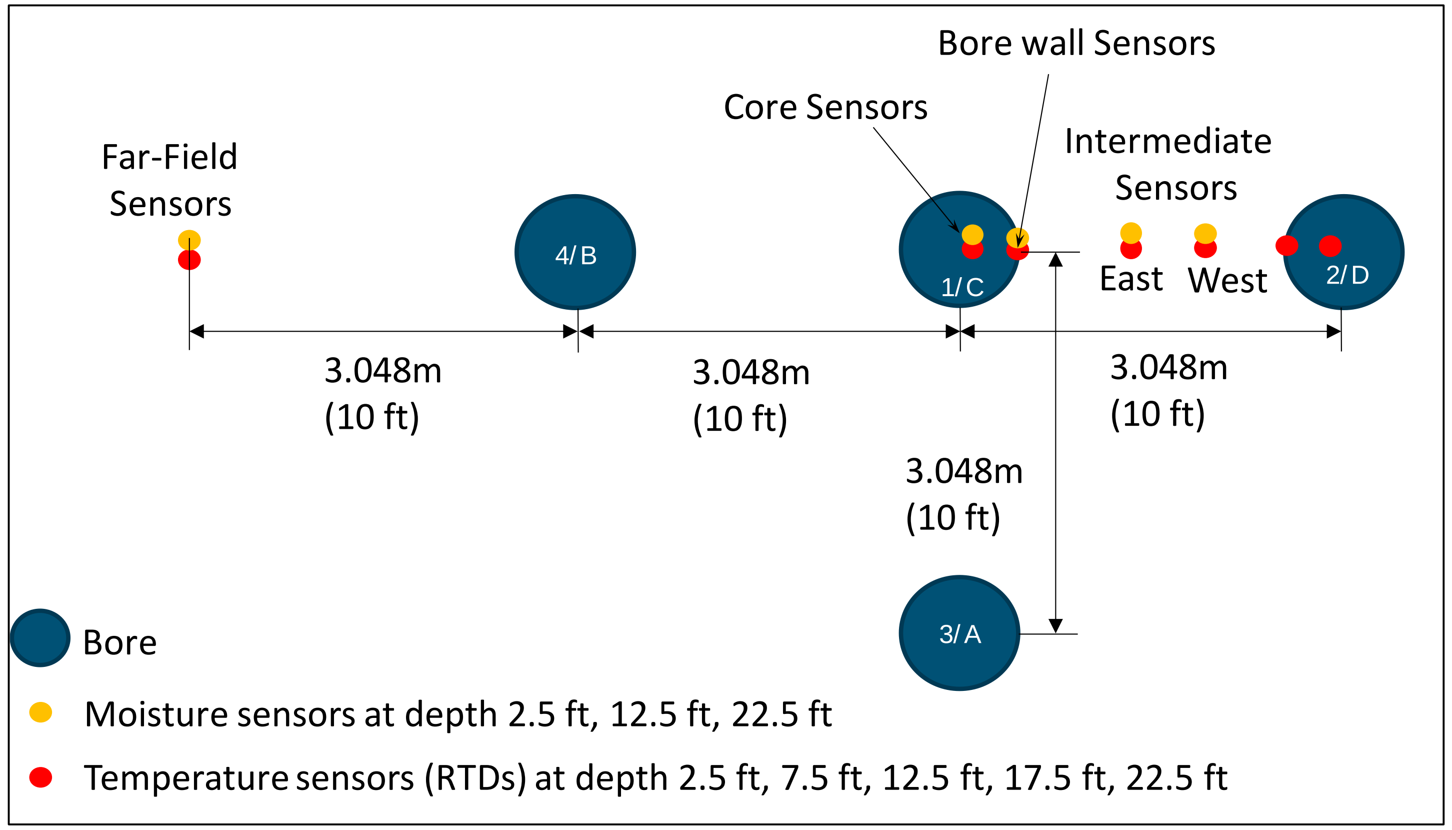
1) CaRM Model improvements (HSH data & CFD)

- RMSD CaRM-He v2 compared to CFD
  - borewall temperature = 0.8˚C (Improved by 35%)
  - core temperature = 0.3˚C (Improved by 27%)
- Borewall contour plot: Difference -2.2 to 0˚C (except for few locations at top and bottom)

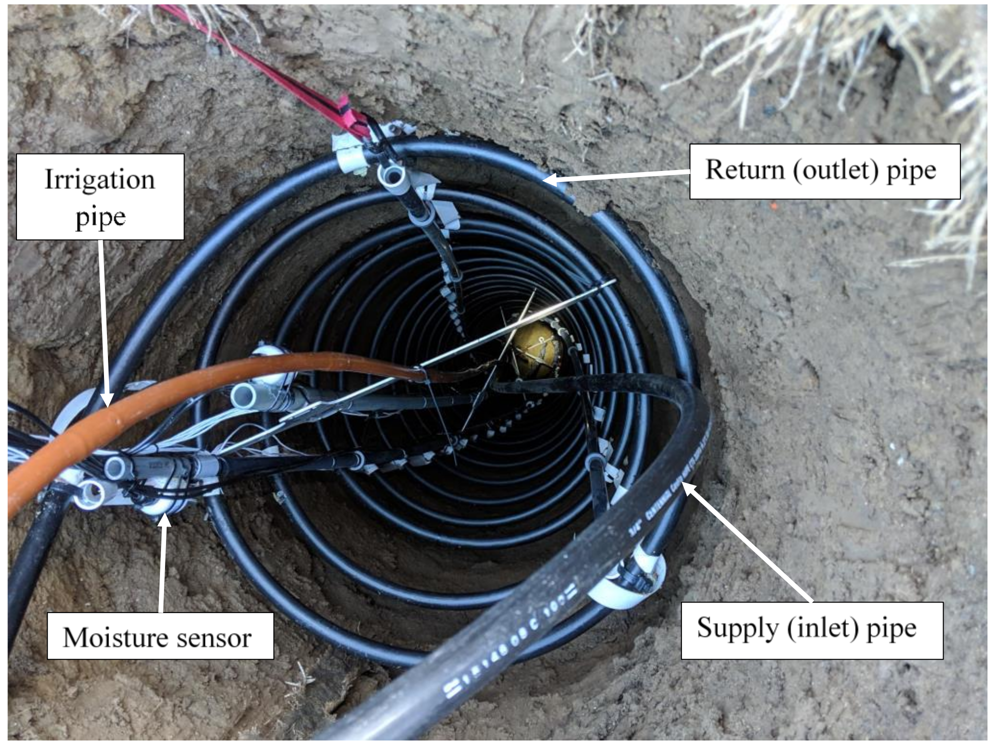




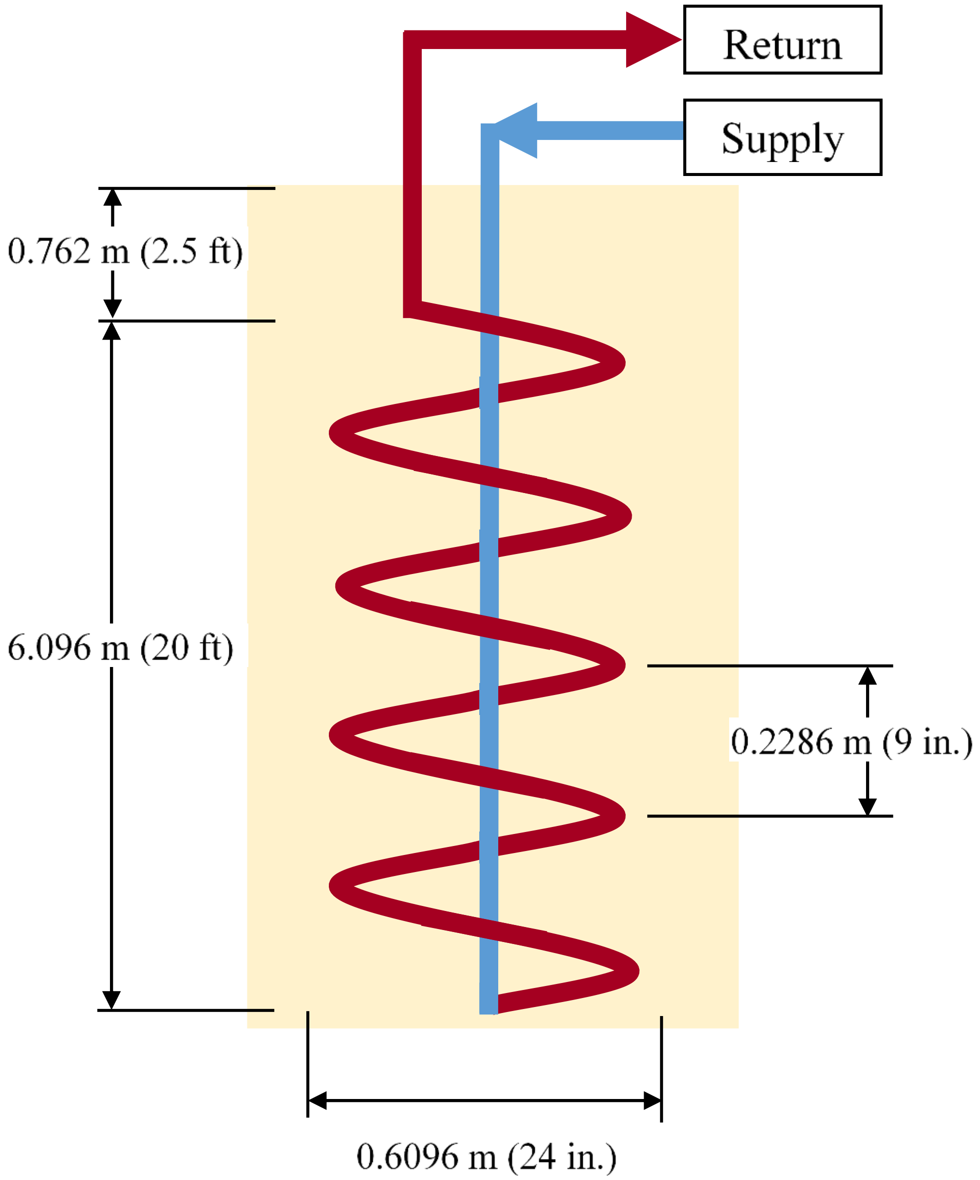
2) Impact of moisture – Test site design



Test site layout & probe locations.



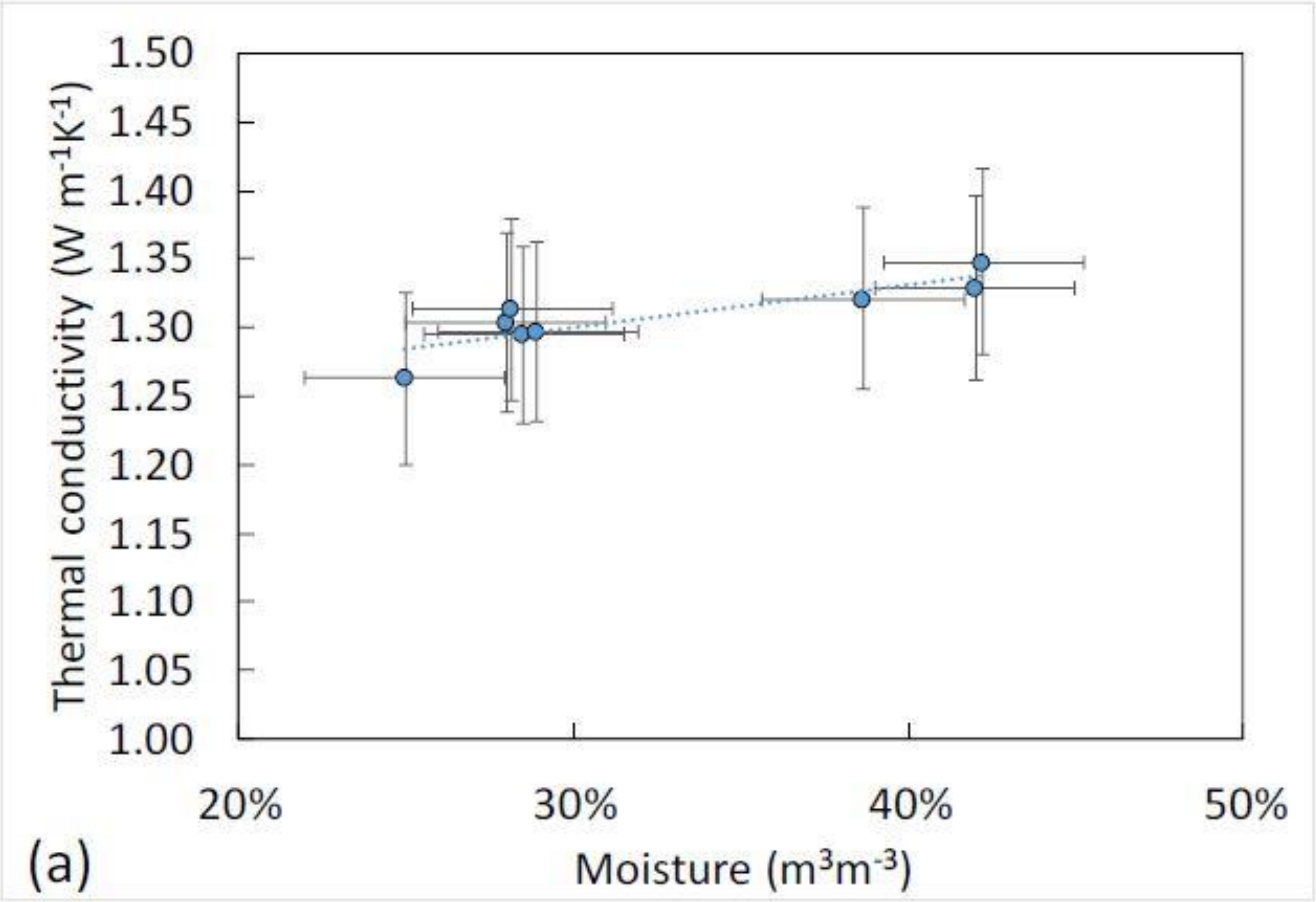
Photograph of top view of GHE 1/C.

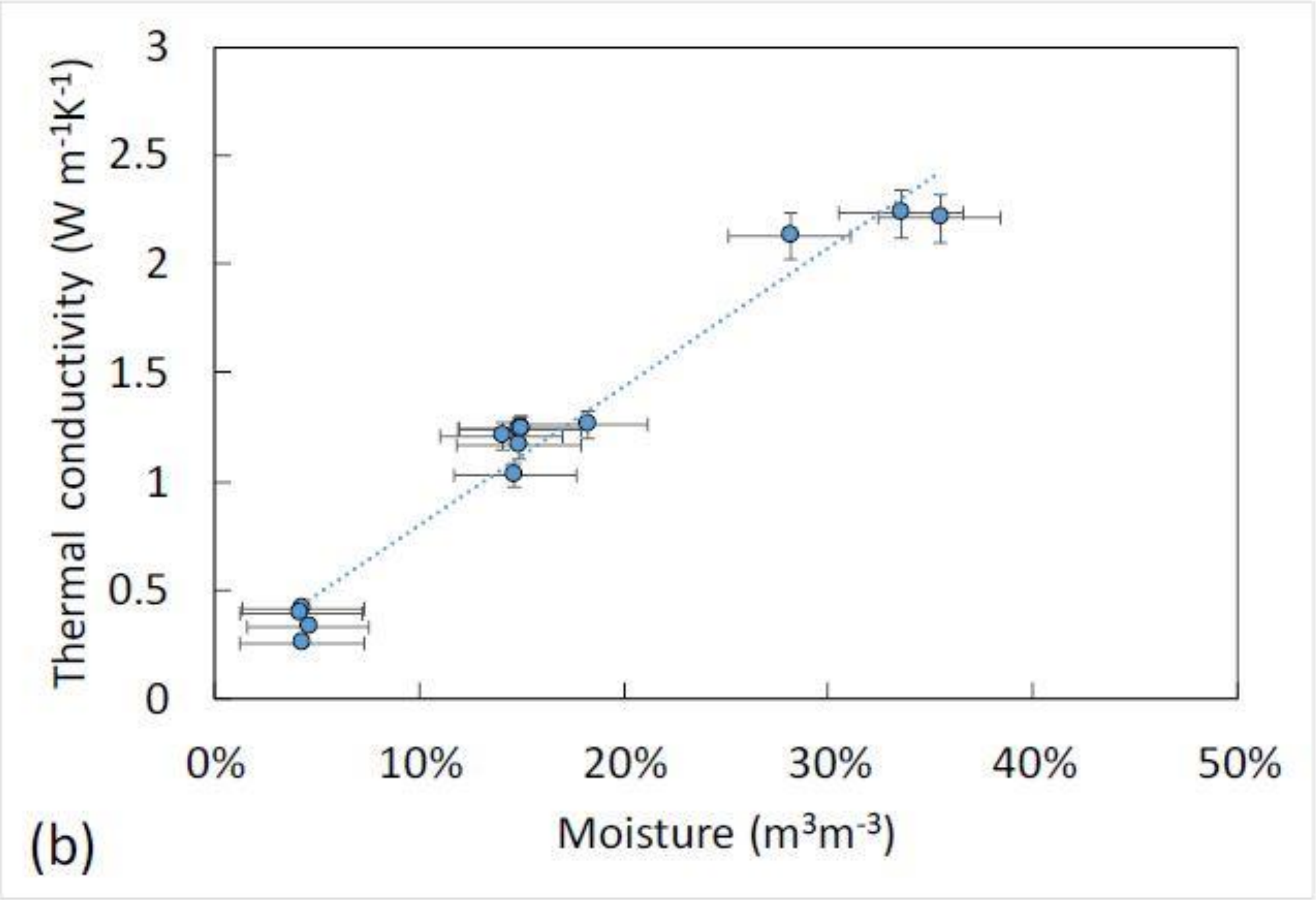


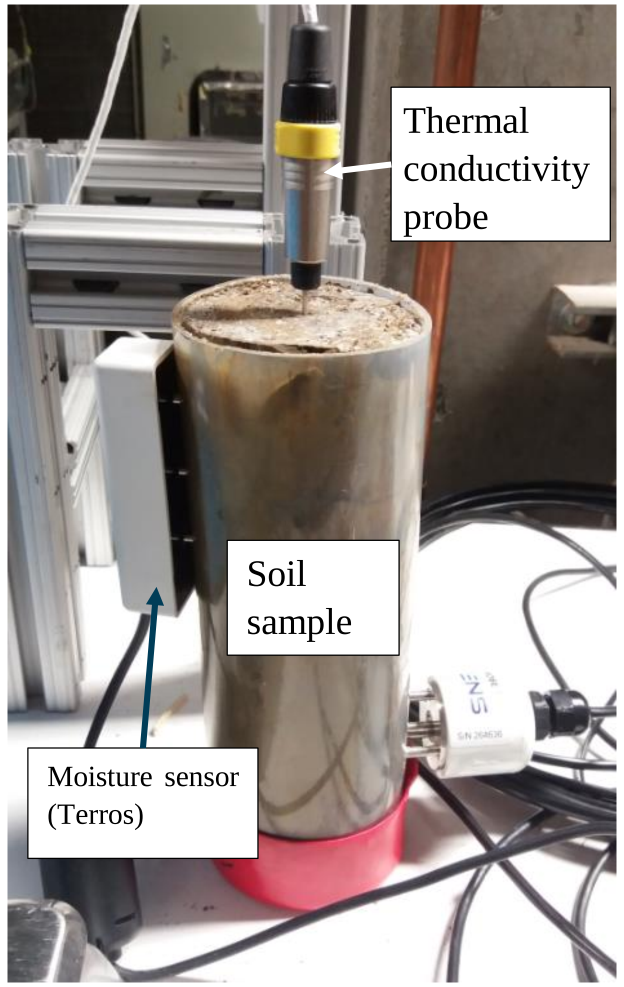
Helical GHE geometry (test site)

2) Impact of moisture – Thermal property results soil & sand

- k_{soil} increases by 4.2%, as moisture increases from 25% to 42%.
- k_{sand} increases by 450% as moisture increases from 4.3% to 35.5%



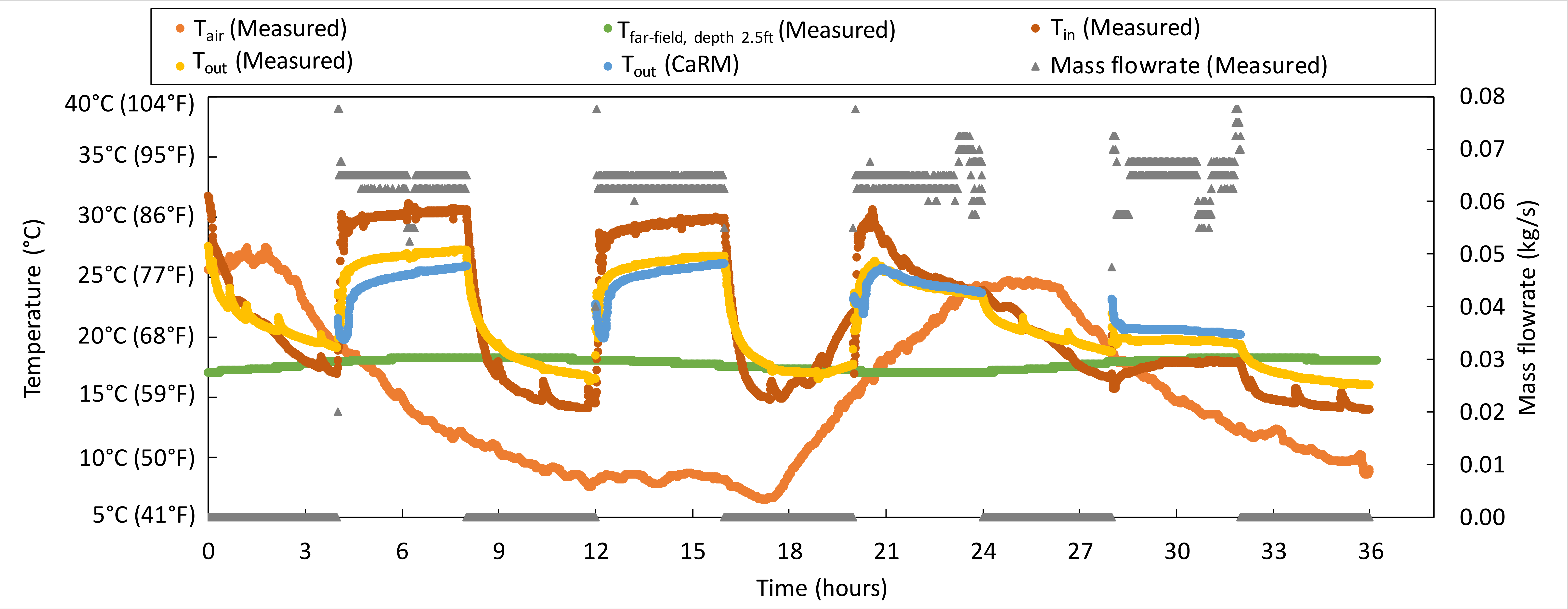




Soil thermal conductivity variation with changes in moisture in (a) soil (b) sand.

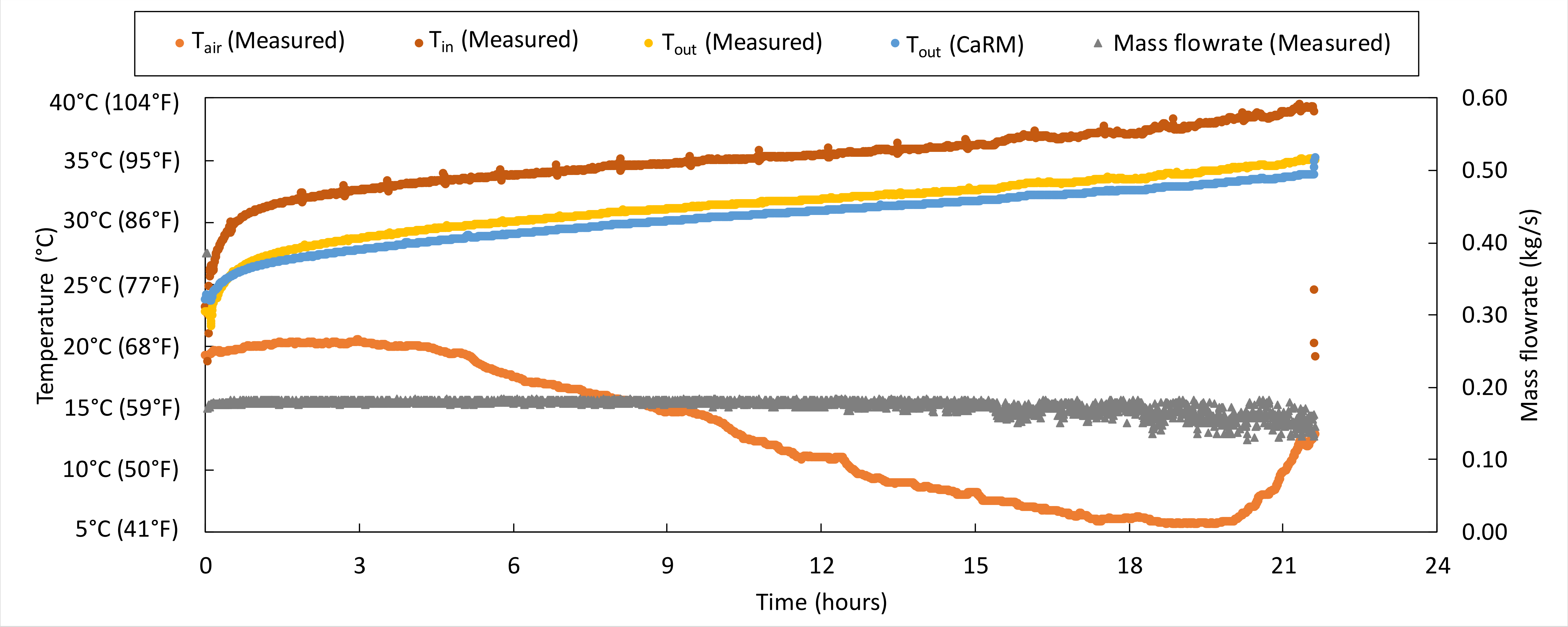
2) Impact of moisture – Single GHE test results

- The Root Mean Square Difference (RMSD) is 1.3°C.



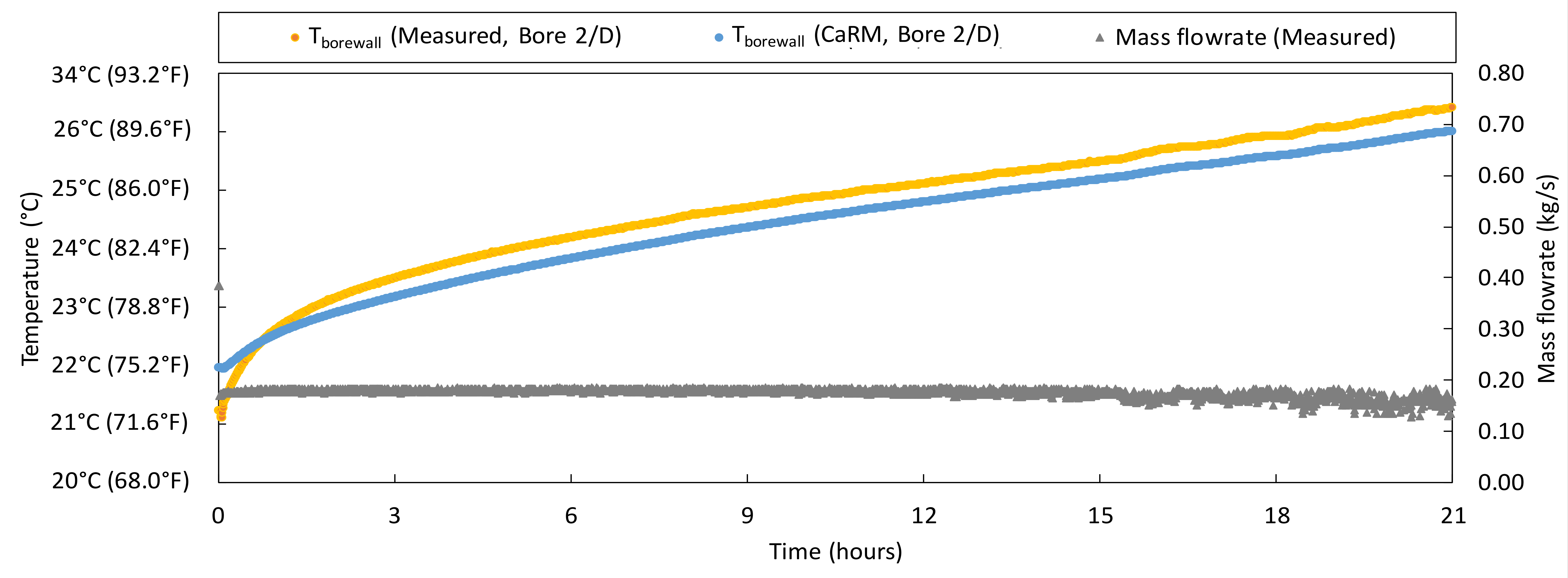
2) Impact of moisture – Multiple GHE test results

- The RMSD between the simulation results and measurements is 1.0°C.



2) Impact of moisture – Multiple GHE test results

- The results match well, however an offset is present. The overall RMSD is 0.7°C.

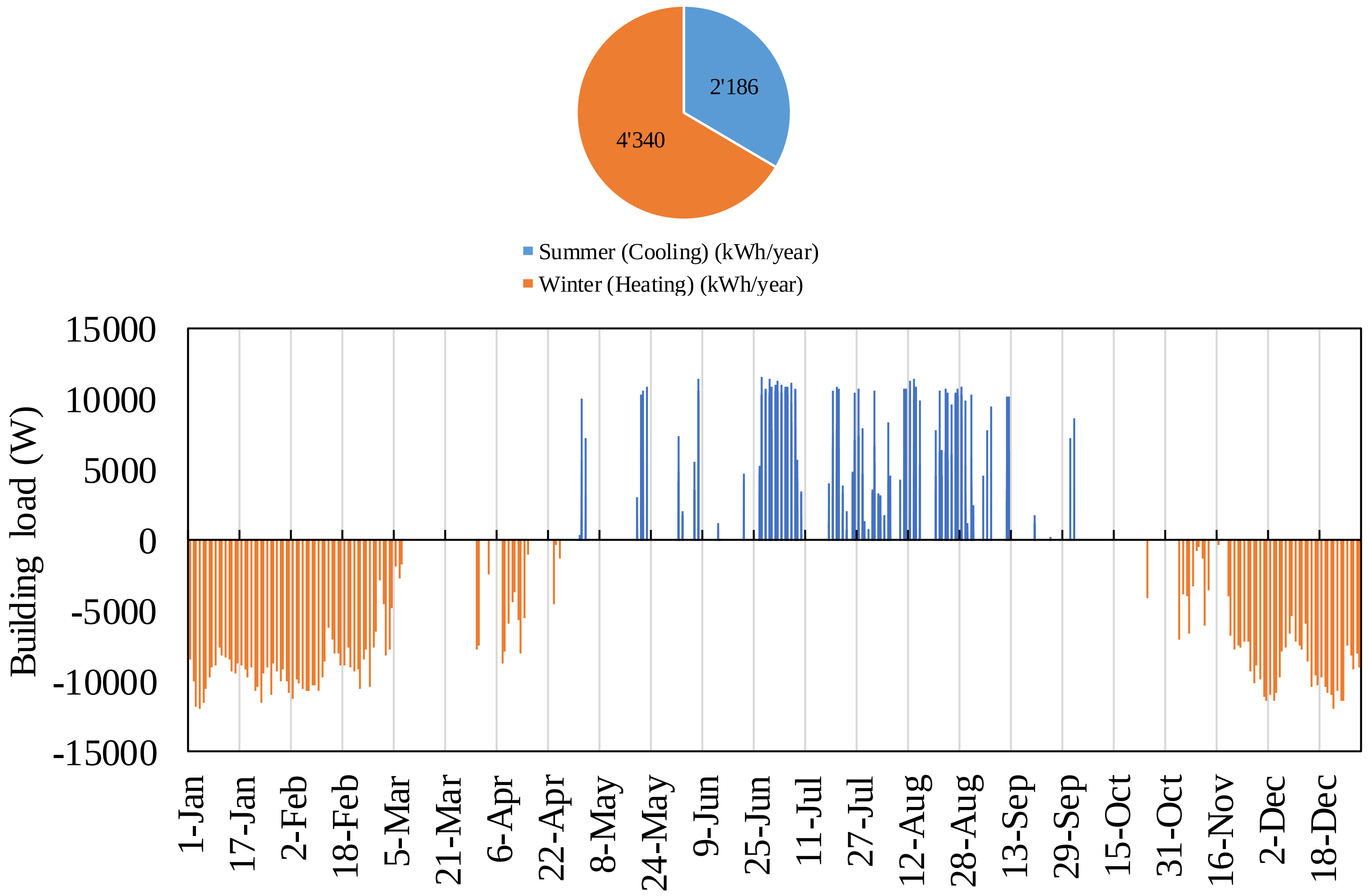


3) Parametric study

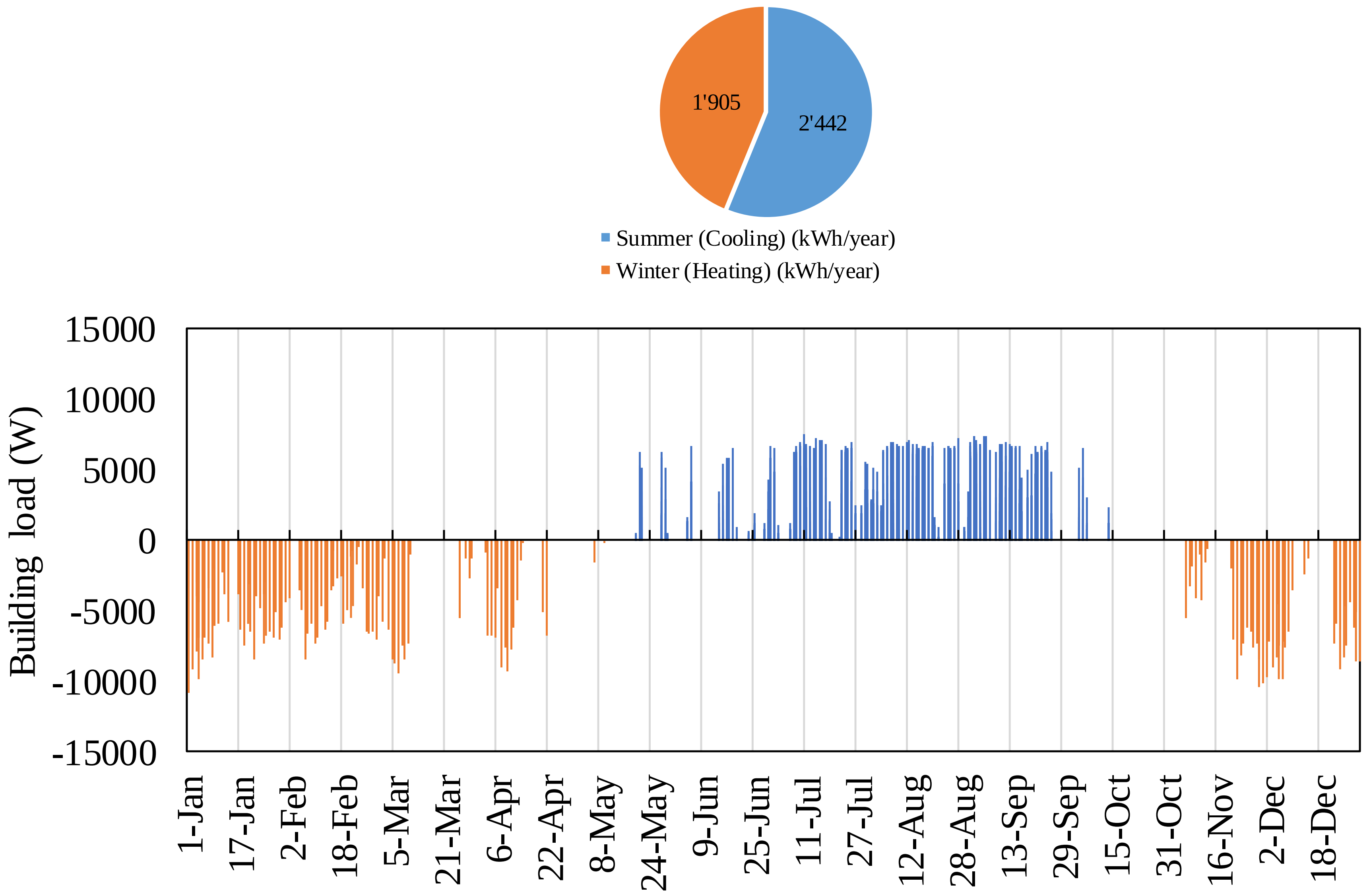
- Heat pump model incorporated in the validated CaRM model.
- CBECC-Res model used to generate building load profile in two CA Climate Zones
- Parametric analysis was performed by varying the following:
  - Spacing
  - Number of GHEs
  - Diameter
  - Arrangement
  - Height
  - Backfill type
- Air-source heat pump used as baseline to evaluate GHE electricity savings

3) Parametric study

- Cumulative summer load: Sacramento and Riverside are within 11% of each other.
- Cumulative winter load: Sacramento is 2.25 times larger than in Riverside.

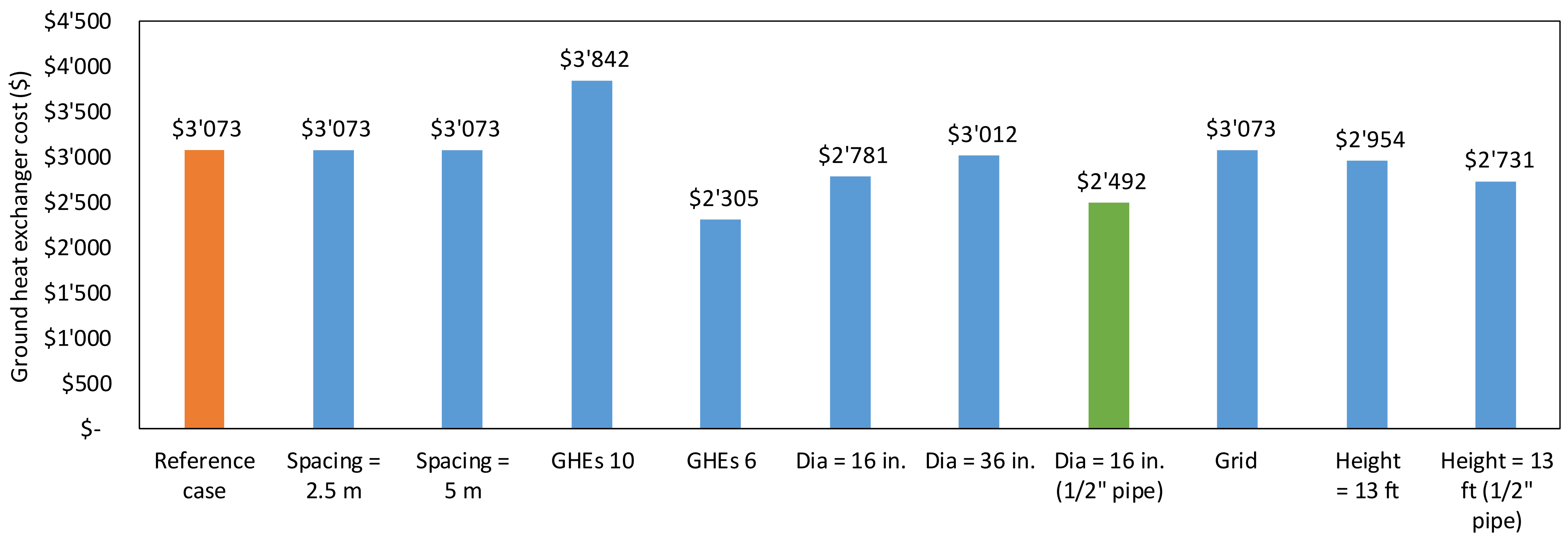


Sacramento CZ12

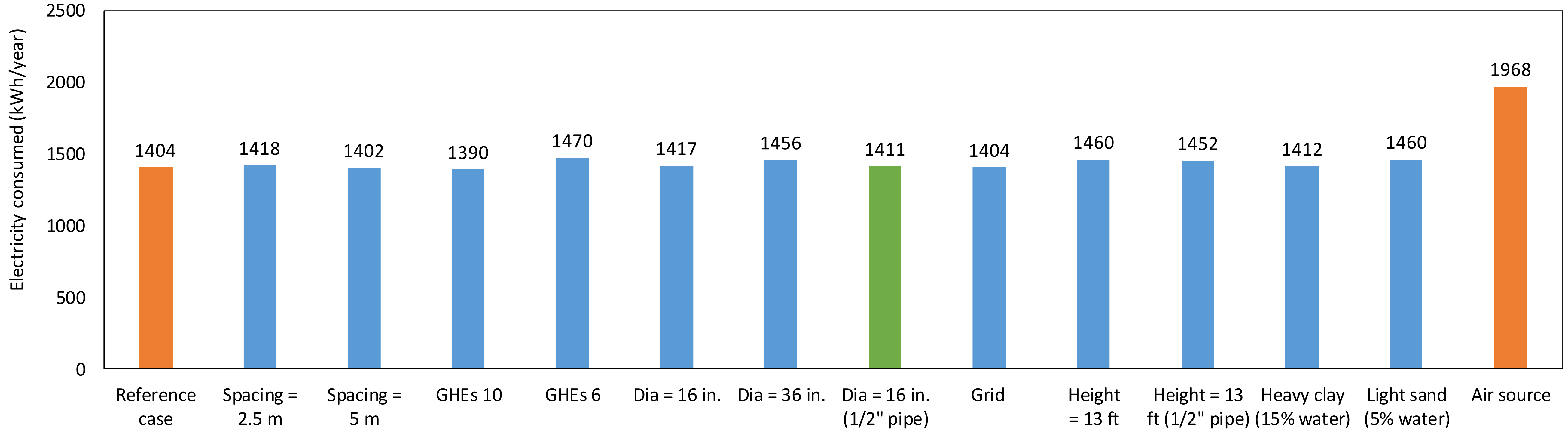


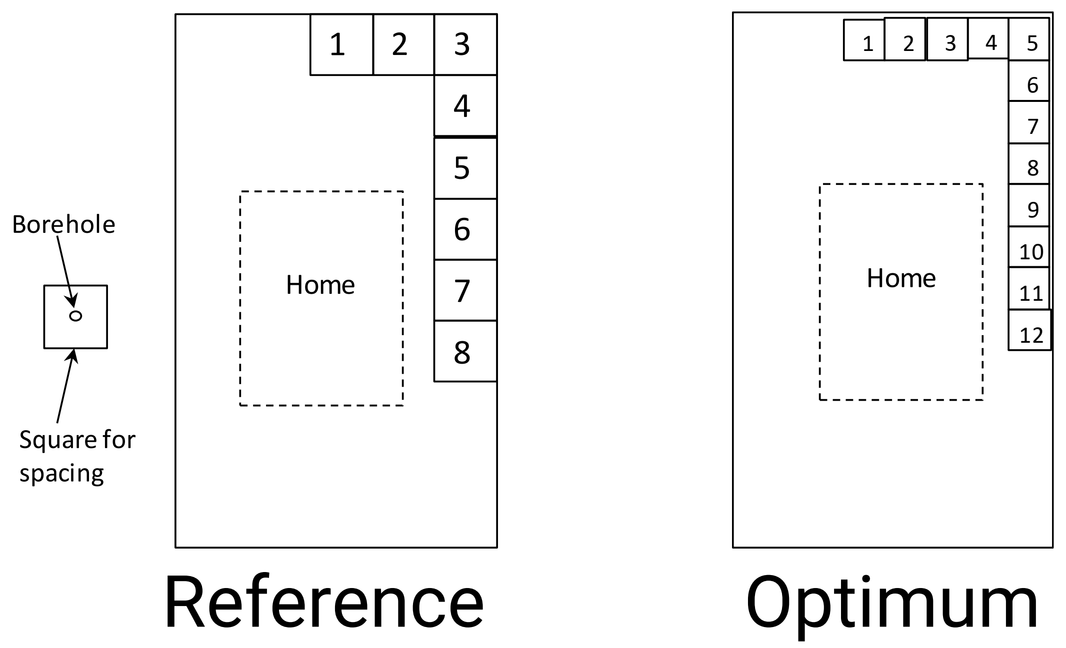
Riverside CZ10

3) Parametric study: Sacramento CZ12



Parameters	Reference	Optimum
Borehole spacing (m)	3.5	2.3
Number of GHEs	8	12
Borehole diameter (in.)	24	16
Pipe diameter (in.)	3/4	1/2
GHE height (ft)	20	20
Cost of 1 GHE	$ 384	$ 208





3) Parametric study: Sacramento CZ12

- Optimum system consumes 28.3% less electricity than air-source

Parameters	Reference	Optimum
Borehole spacing (m)	3.5	2.3
Number of GHEs	8	12
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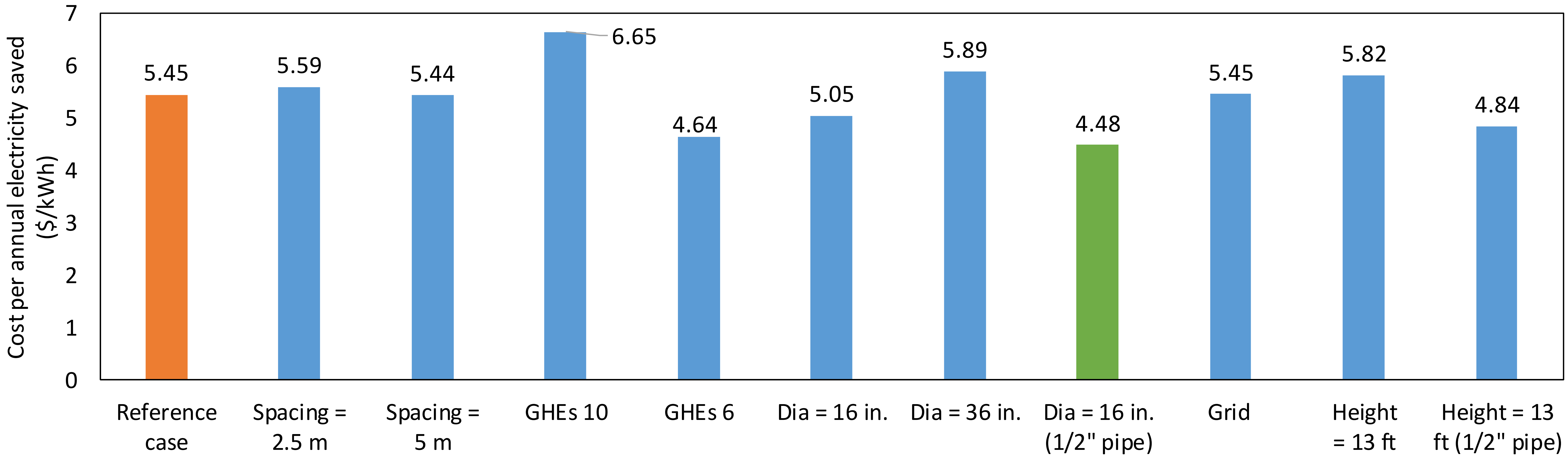
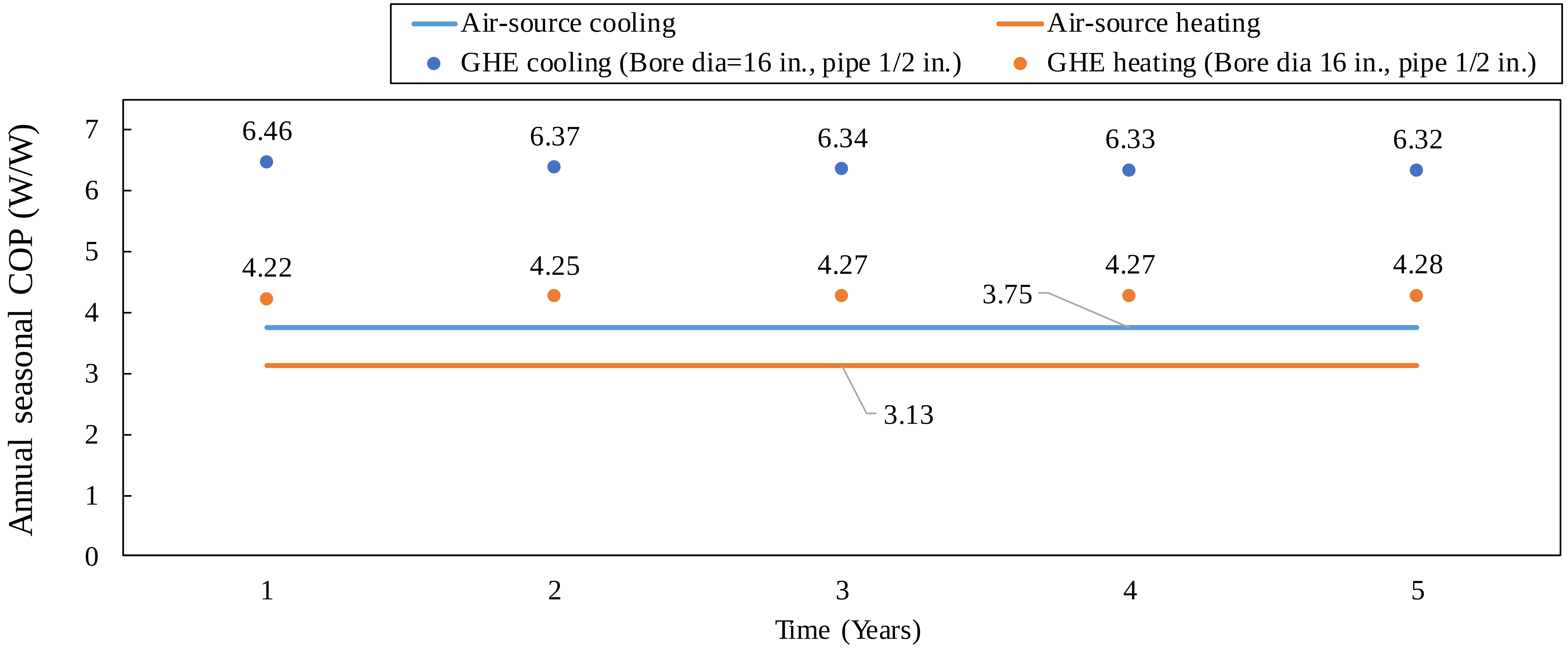


3) Parametric study: Sacramento CZ12

Optimum system seasonal COP compared to air-source

- Heating: 36% better
- Cooling: 70% better

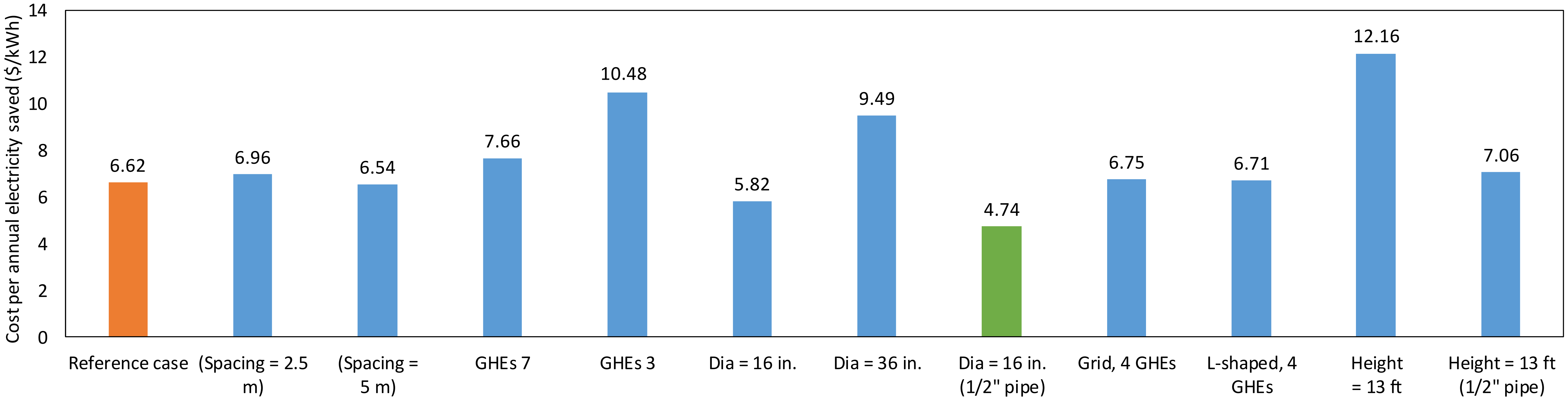
Parameters	Optimum
Borehole spacing (m)	2.3
Number of GHEs	12
Borehole diameter (in.)	16
Pipe diameter (in.)	1/2
GHE height (ft)	20
Cost of 1 GHE	$ 208



3) Parametric study: Riverside CZ10

- Optimum system consumes 28.5% less electricity than air-source.
- Optimum system seasonal COP compared to air-source
  - Cooling: 48% better
  - Heating: 43% better

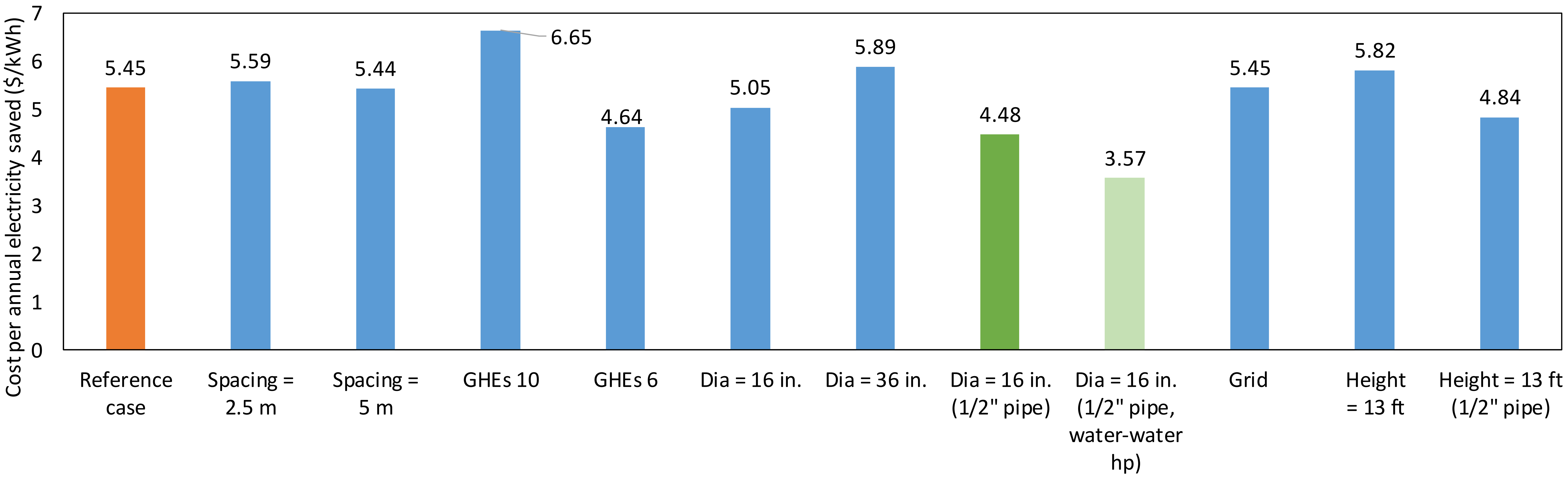
Parameters	Reference	Optimum
Borehole spacing (m)	3.5	2.3
Number of GHEs	5	8
Borehole diameter (in.)	24	16
Pipe diameter (in.)	3/4	1/2
GHE height (ft)	20	20
Cost of 1 GHE	$ 384	$ 208



3) Parametric study: Sacramento

Conservative estimates:

- Heat pump performance adjusted for 15% propylene glycol
- Electricity consumed by circulation pump (efficiency = 50%)
- Water-water heat pump result is 20% better than air-water heat pump



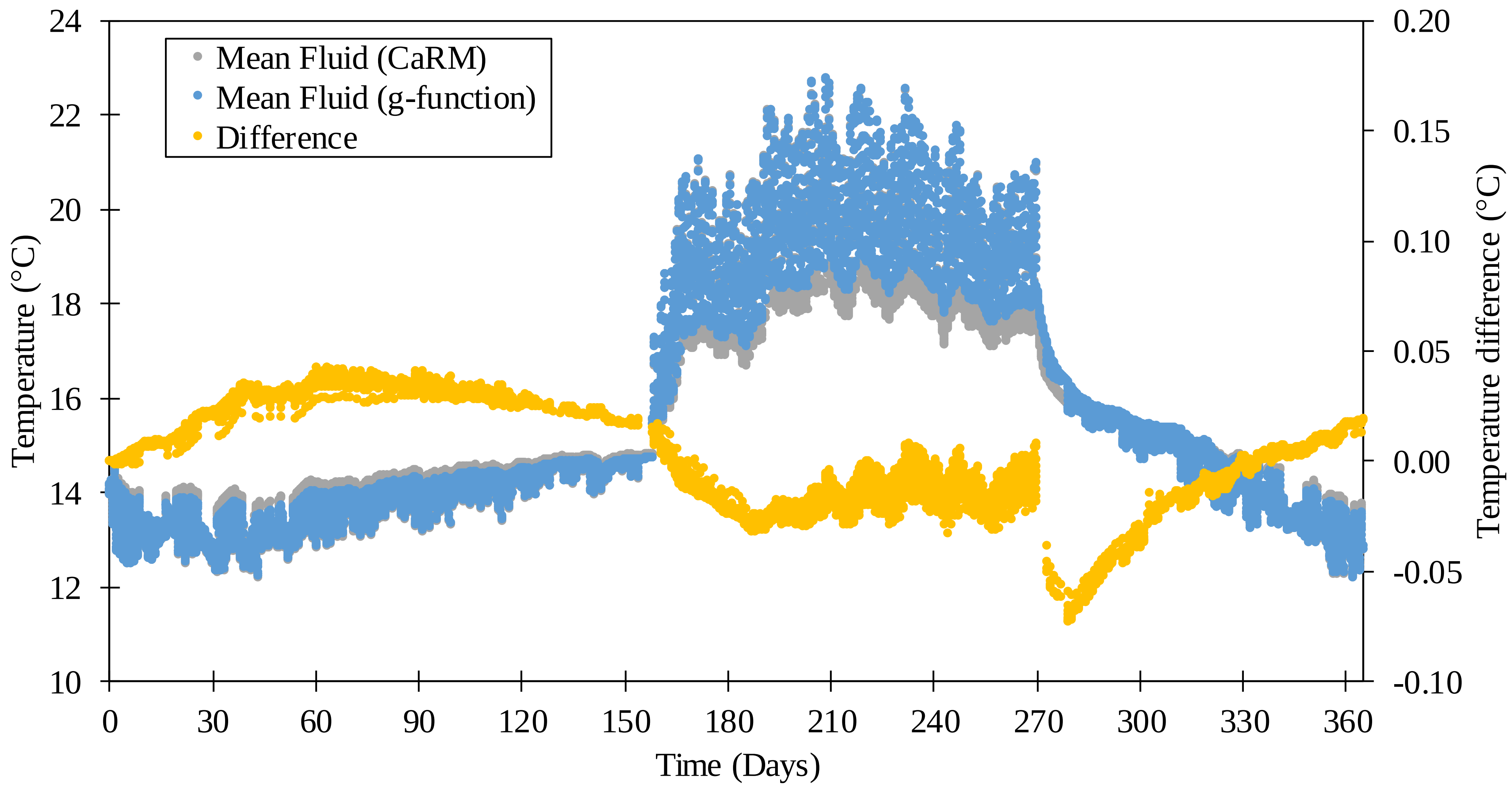
4) Helical GHE response factor development

- G-functions: dimensionless resistance. Provide the temperature of the borehole wall (T_b) for a given heat flux (Q', W/m) at a given time step:
- EnergyPlus relies on G-functions to model GHEs.

$$T_b - T_o = Q' \times R$$

$$g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) = \frac{2\pi k\{T_b - T_o\}}{Q'} = 2\pi k . R$$

$$t_s = \frac{H^2}{9\alpha}$$



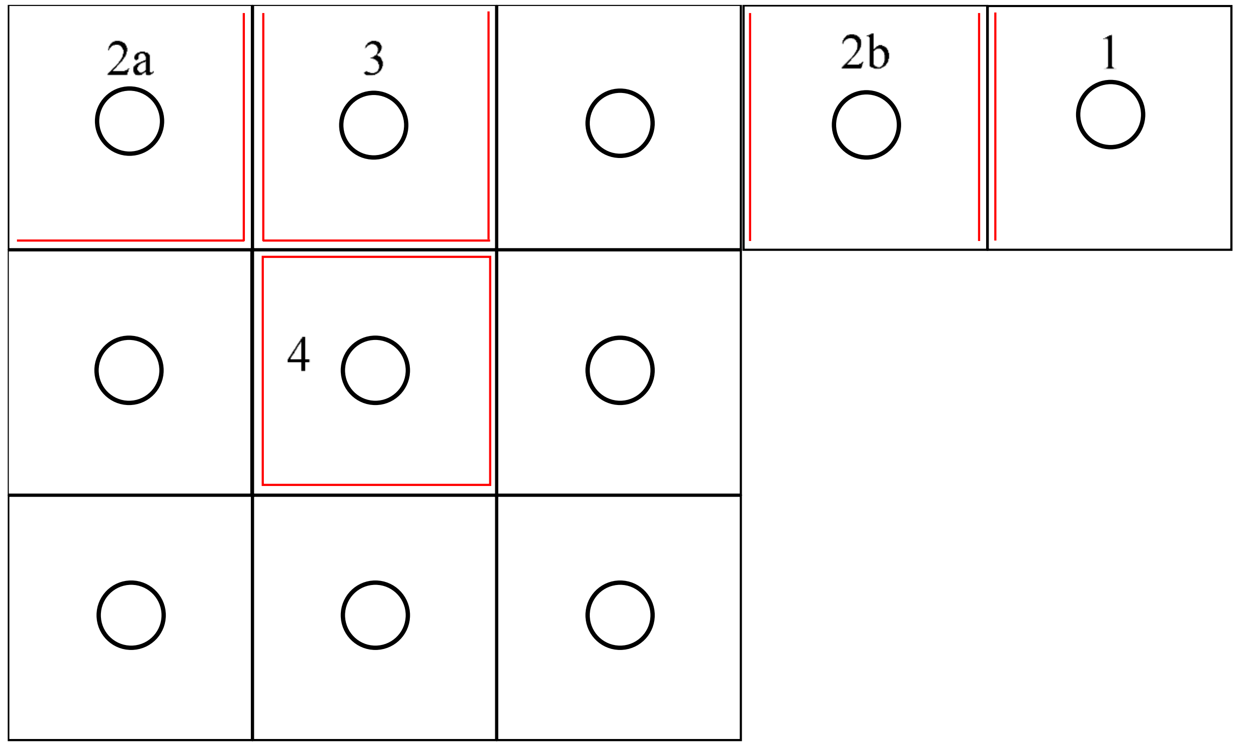
4) Helical GHE response factor development

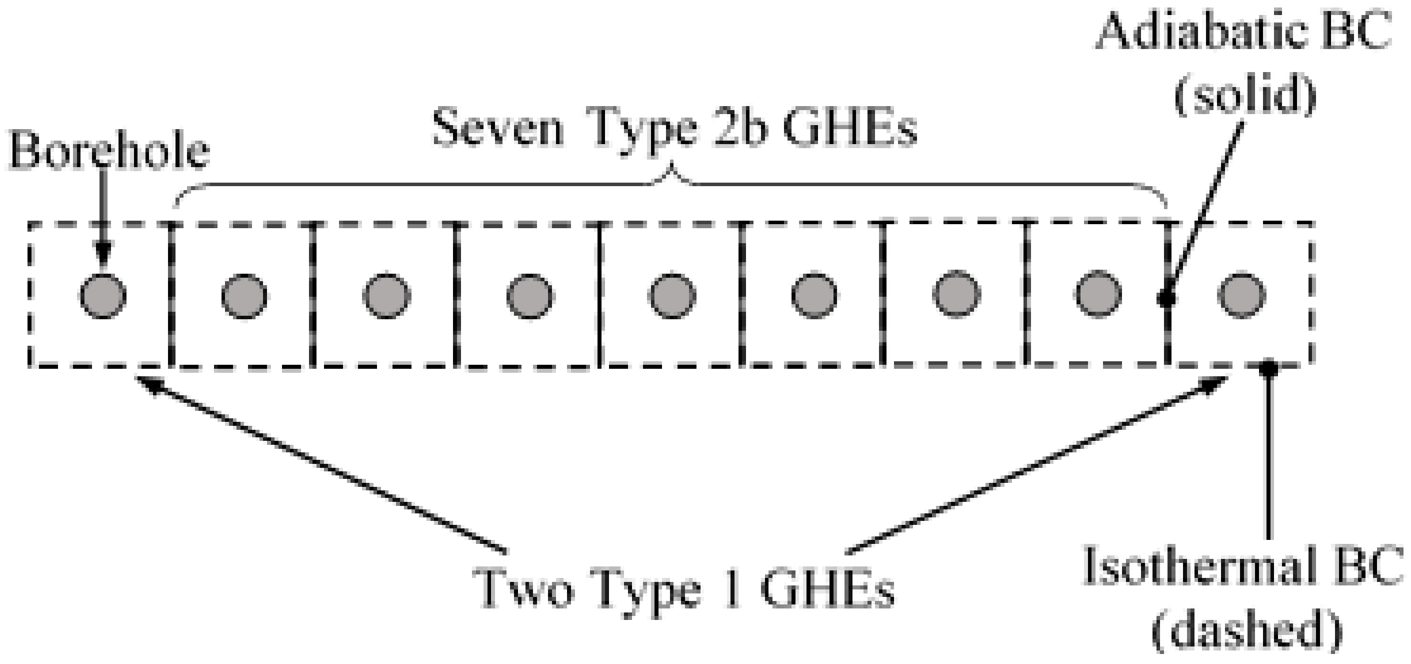
» Multiple GHE g-function:
- Average difference (10 years)= 0.09%
- Combined g is weighted average of individual g.

$$g = x_1 . g_1 + x_{2b} . g_{2b}$$

$$g = \left(\frac{2}{9}\right) . g_1 + \left(\frac{7}{9}\right) . g_{2b}$$

» CaRM was used to generate G-functions for all boundary conditions for following parameters.
- Borehole diameter
- GHE height
- Pitch (to ensure independence)
- Backfill properties





Conclusion

- CaRM model improved using CFD model and HSH data.
- Impact of soil moisture on GHE performance was measured and incorporated in the modeling approach.
- Parametric study of GHE carried out. Results show significant electricity saving over baseline air source heat pumps.
- Response factors from CaRM generated. These allow building simulation software to model Helical GHEs.

Papers

Published

- A. Najib, A. Zarrella, V. Narayanan, P. Grant, C. Harrington and R. Larson, "Modeling and Parametric Study of Large Diameter Shallow Bore Helical Ground Heat Exchanger." ASHRAE Transactions, vol. 125, no. 1, 2019, p. 255+.
- A. Najib, A. Zarrella, V. Narayanan, P. Grant and C. Harrington, "A revised capacitance resistance model for large diameter shallow bore ground heat exchanger," Applied Thermal Engineering, vol. 162, p. 114305, 2019.
- A. Najib, C. Harrington, D. Springer, M. Slater, A. Zarrella, V. Narayanan, "Field tests of large diameter shallow bore helical ground heat exchanger with simulated heating loads," Accepted for ASHRAE Summer Conference, Austin June 2020.

To submit:

- Parametric study journal paper
- G-function journal paper
- Field tests journal paper

Questions?

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I am also thankful to my close friend and former supervisor, Nadir Husain who motivated me to pursue a PhD and supported me throughout.

Words can express neither my gratitude nor my admiration for my beloved wife, Erum. Her care, dedication and hard work towards nurturing our family over the last four years easily amounts to the work required for ten PhDs (conservative estimate). She is also responsible for my life's single greatest blessing and joy i.e. our amazing son Arham. I am also very thankful to my father and to all my in-laws for their help and support (especially Erum's mom and eldest siblings, Zohra and Mobeen).

Lastly, my heartfelt gratitude and prayers go out to my mother (Kausar, named after a river in heaven) and younger brother (Danish, which means intelligence). Their memories have been a source of inspiration for me. My mom was also my 1st grade teacher and her lessons continue to shape my future.