U.S. DEPARTMENT of ENERGY | Federal Energy Management Program

Geothermal Energy: Design and Implementation Strategies

T02-S05, August 6th, 2025

FEMP Summer CAMP (Courses Aligned with Mission Priorities)

Eric Nyenhuis, PE

Director, Energy Consulting
Southland Industries

Agenda

- Session Learning Objectives
- What are geothermal district energy systems (geo-DES)
- Design process
- Building integration considerations
- Types of Geothermal Energy Storage
- Grid Amplified Building Energy Seasonal Storage (GABESS) and Thermal Energy Network (TEN)
- Examples in North America and Europe and Next Generation Projects
- Conclusion and Q&A

Session Learning Outcomes

1. Evaluate key design and implementation steps for district geothermal systems.
2. Recognize feasibility and engineering factors in geothermal projects.
3. Identify O&M considerations for geothermal system operations.
4. Recognize a successful example of on-site geothermal resilience.

Amy Allen, Ph.D., P.E.

Research Engineer

National Renewable Energy Laboratory

Outline

What are geothermal district energy systems (geo-DES)

What are ground heat exchangers (GHE)

Design process

Thermal loads

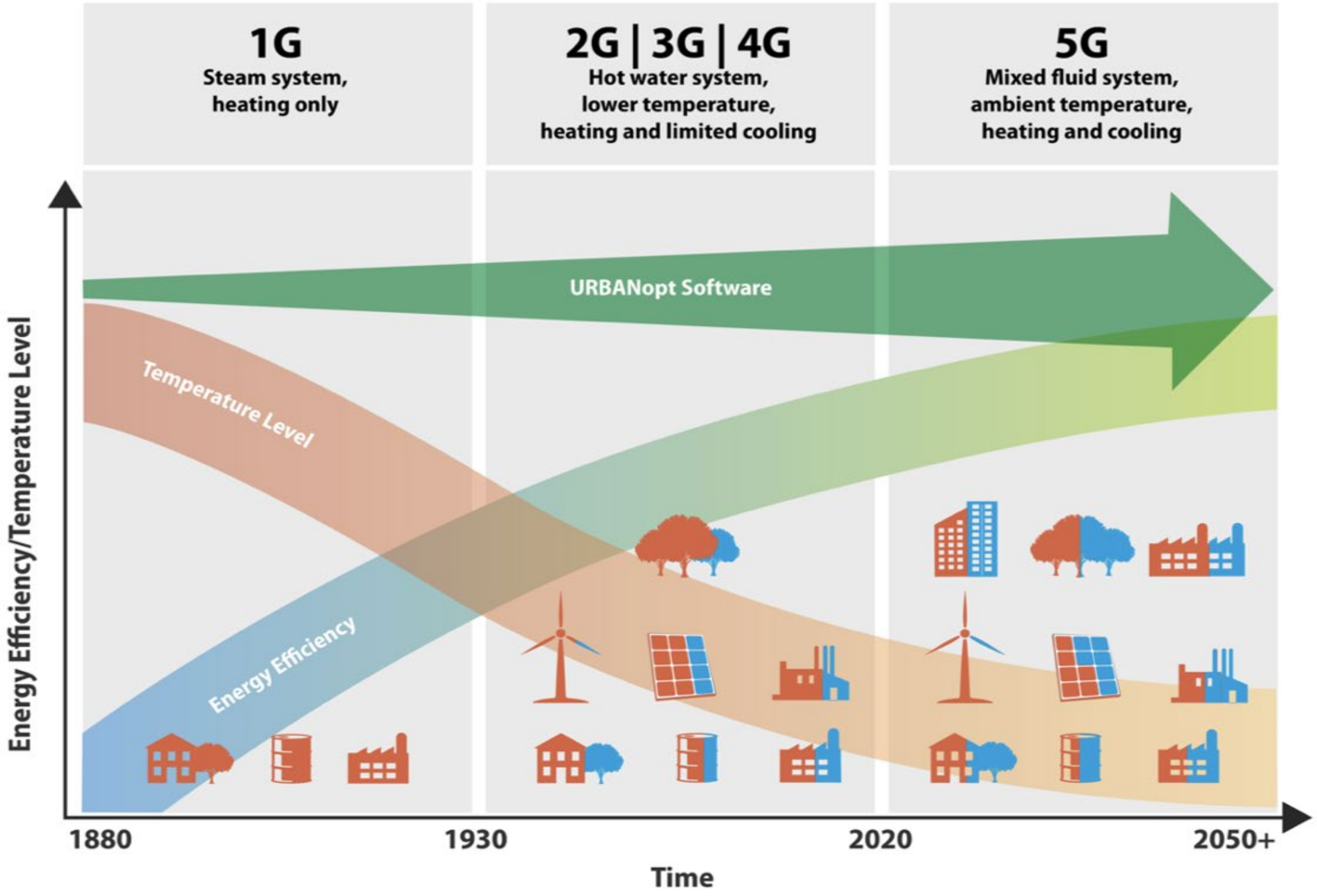
Building integration considerations

GHE sizing

Geo-DES modeling

Thermal response test (TRT) considerations

Evolution of District Thermal Energy Systems



- Newer “generations” of district thermal energy systems use water at increasingly moderate temperatures, rather than steam, as the working fluid
- More moderate fluid temperatures result in greater efficiency

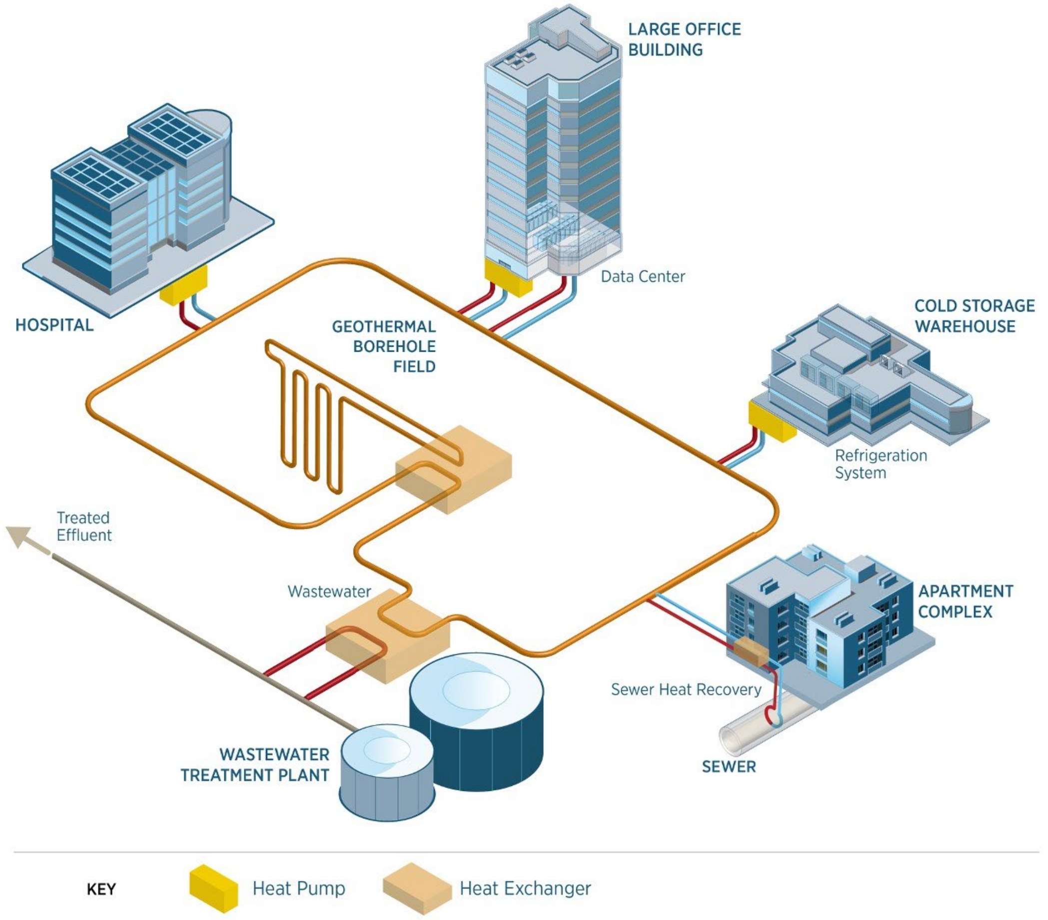
Figure Credit: Marjorie Schott (NREL)

Geothermal District Energy Systems (Geo-DES)

Incorporate ground heat exchangers (GHE) or other geothermal resources

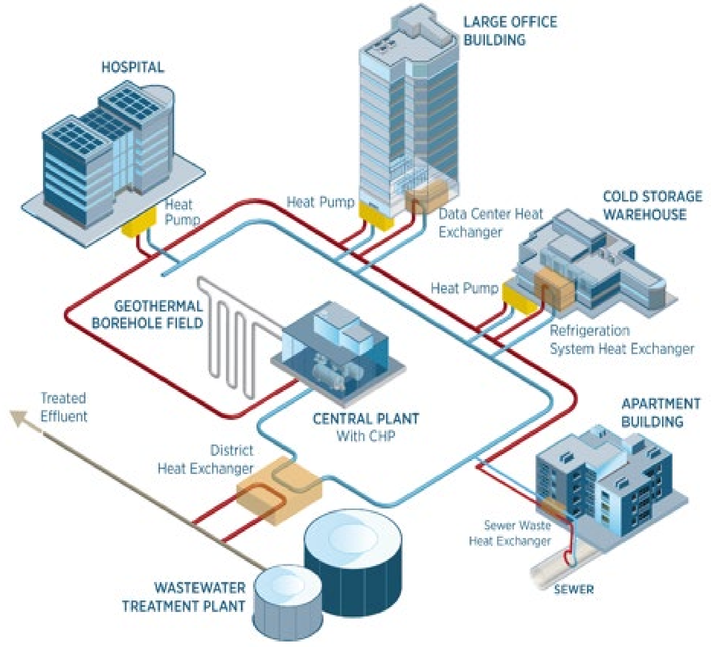
Can exist in four-pipe (hot and chilled water) or ambient loop-style configurations

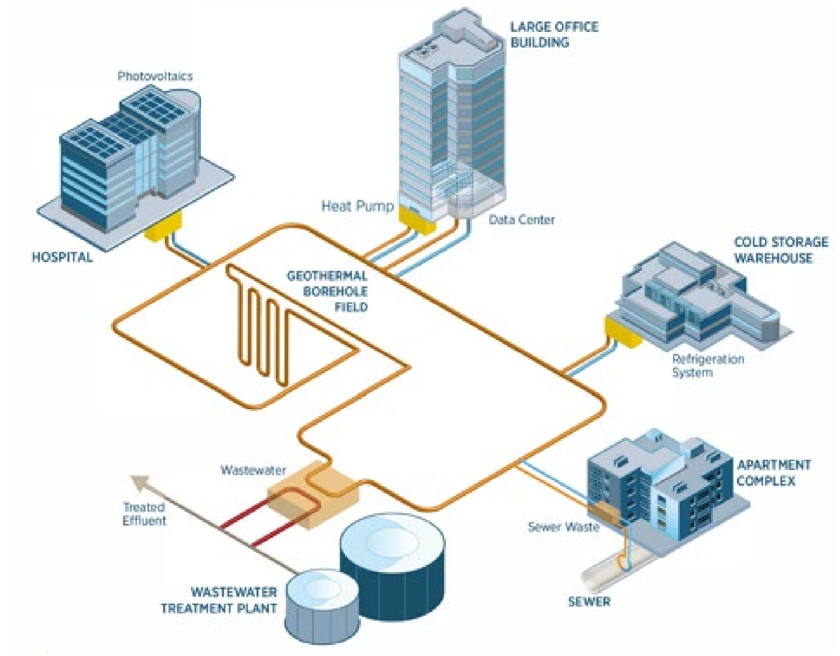
Save energy through efficient water-source heat pump performance, as well as load balancing



Right: Illustration of Geo-DES in ambient loop-style configuration. Figure credit: Marjorie Schott (NREL)

Selected Geo-DES Configurations





Geo-DES in 2-pipe (left) and 1-pipe (right) configurations.
Figure Credit: Marjorie Schott, NREL.

- Ambient-loop style networks can be configured as single-pipe or two-pipe
- Circulation pumps can be centralized and/or distributed
- "Energy transfer stations" (ETS) connect loads to the network
- Connections to higher-temperature systems, such as combined heat and power (CHP), can be included

District Energy Systems in Operation

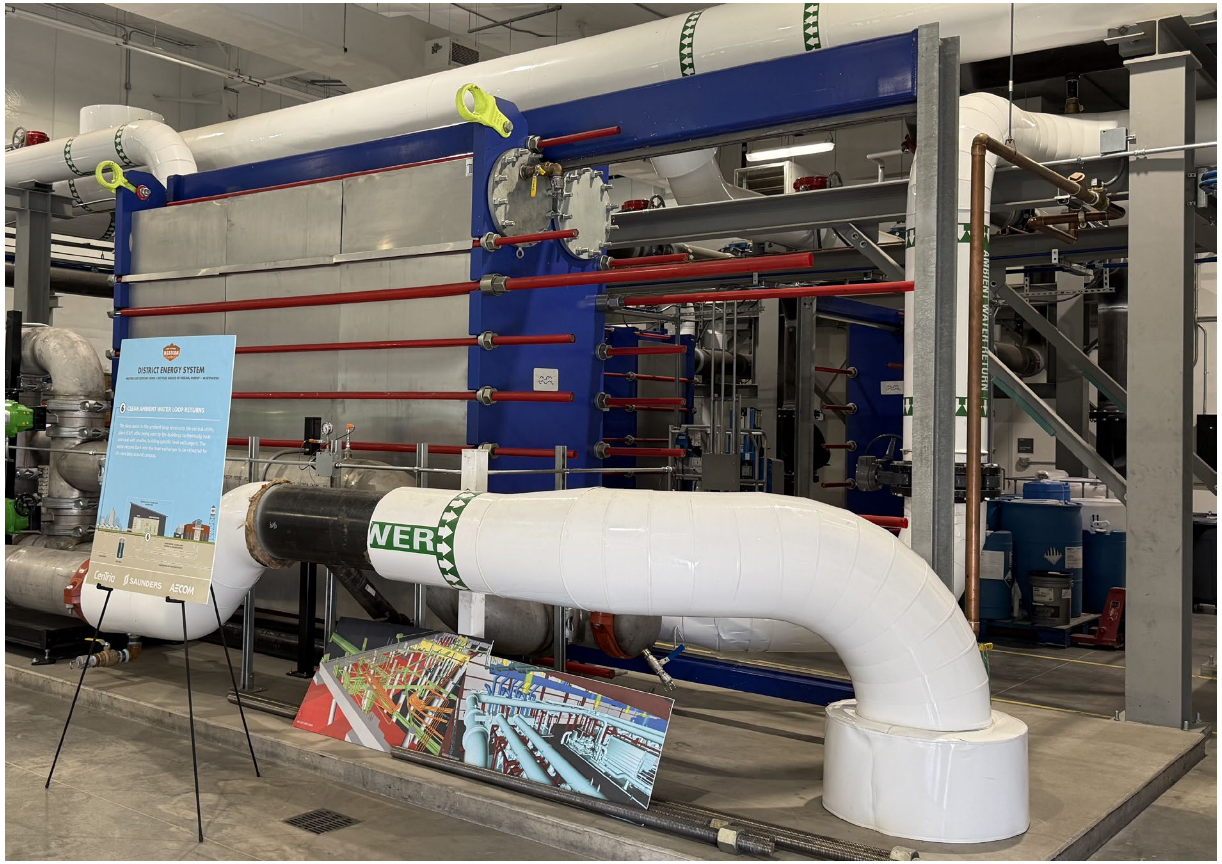


Photo Credit: Nicholas Long

- Heat exchanger serving wastewater heat recovery supplying ambient loop at the National Western Center (Denver, CO)
- System serves 3.8 MW peak load, and 90% of the annual heating and cooling needs for a 1 million sq.ft. campus
- Wastewater is a near-ambient temperature heat source and sink that can be integrated with geo-DES

Horizontal Ground Heat Exchangers

- Installed close to the surface; can often be installed with excavators, backhoes, or chain trenchers
- Requires more land area (can be well suited for sites where area is available)
- Cheaper to install than vertical boreholes
- Long-term soil temperature changes not a risk, but affected by variation in weather, as well as rainfall, etc.
- Directional drilling also an option (for example, to install under parking lot)

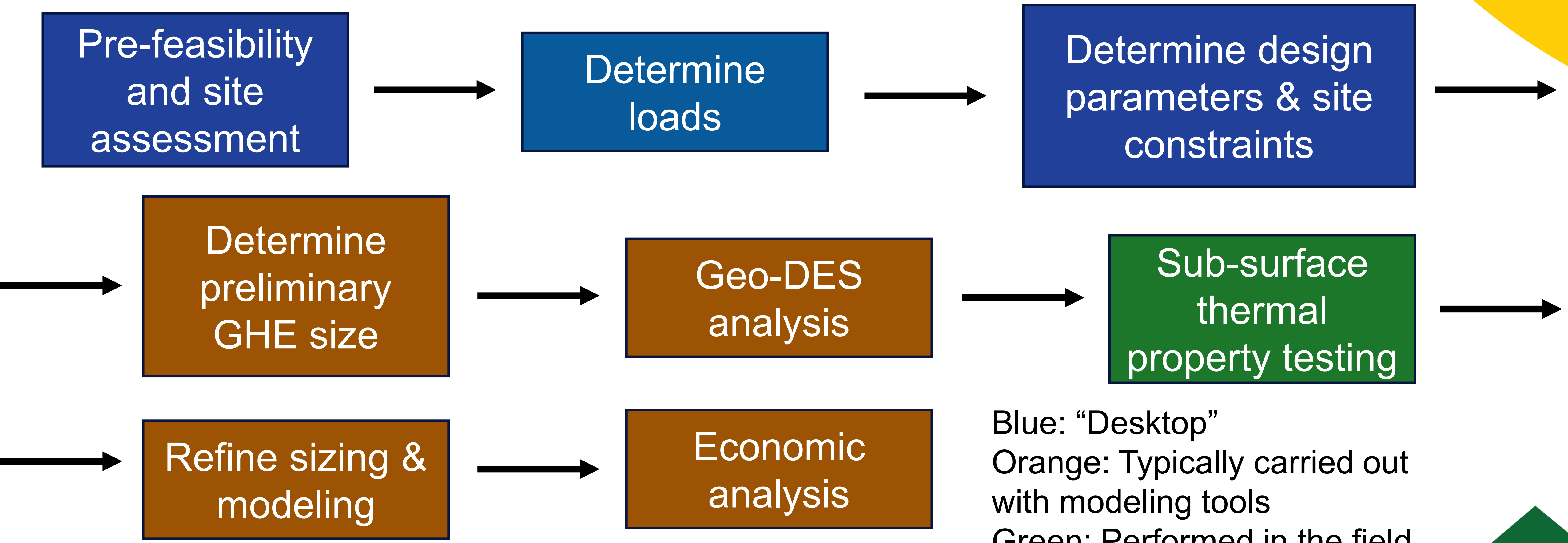
Horizontal GHE installed to serve district energy system. Photo courtesy of Matt Mitchell.

Vertical Ground Heat Exchangers

- Typically use boreholes of 300 + ft in depth to access stable ground temperatures year-round
- Boreholes generally grouted with bentonite and/or cementitious grout
- Soil temperatures surrounding GHE can change over time depending on system loads. Considerations must be taken to ensure design accounts for temperature drift.
- Requires drilling, which has high costs
- Directional drilling is an option to minimize surface impacts

Vertical GHE wells installed to serve district energy system before tie in. Photo courtesy of Matt Mitchell.

Design Process



Blue: “Desktop”
Orange: Typically carried out with modeling tools
Green: Performed in the field

Thermal Loads

Building heating, cooling, and domestic hot water load profiles required for analysis of geo-DES, ideally at an hourly or sub-hourly level

Modeled or metered (existing building) data can be used

- For existing buildings, BMS data on temperatures and flow rates on hydronic loops can be used to calculate thermal loads

High thermal load diversity is advantageous

Consider load reduction measures first:

- Building load reduction measures can enable "downsizing" of equipment, as well as enhancing compatibility with water-source heat pumps

Building and Loop Considerations

In ambient loop configurations, distributed water-to-water or water-to-air heat pumps can be used

In chilled water/hot water (four-pipe) style systems, centralized water-to-water heat pumps are used

For building-level hydronic systems, temperature compatibility is a consideration

Working fluid

- Addition of anti-freeze may be necessary
- Anti-freeze has a pump energy penalty and may face regulatory restrictions, but increases loop temperature range, and can reduce borefield size relative to water

GHE Sizing

A variety of sizing tools exist

GHEDesigner: flexible and robust sizing of GHEs, given space and temperature constraints, to meet building loads

- Open source

Key inputs:

- Soil properties
- Maximum borehole depth
- Borehole spacing
- Pipe properties
- Geometric constraints
- Temperature constraints
- Building thermal loads

Outputs:

- Borefield dimensions
- Parameters needed for GHE modeling.

Example Sizing Results

Peak Loads (kW)		Cumulative Load Ratio	Working Fluid	Number of Boreholes	Total Length (ft)	Area (ft^2)
Htg.	Clg.					
750	500	1.17	Water	603	85,000	740,000
750	500	1.17	Ethylene glycol/water	245	39,000	72,000
550	500	0.27	Ethylene glycol/water	415	65,000	126,000

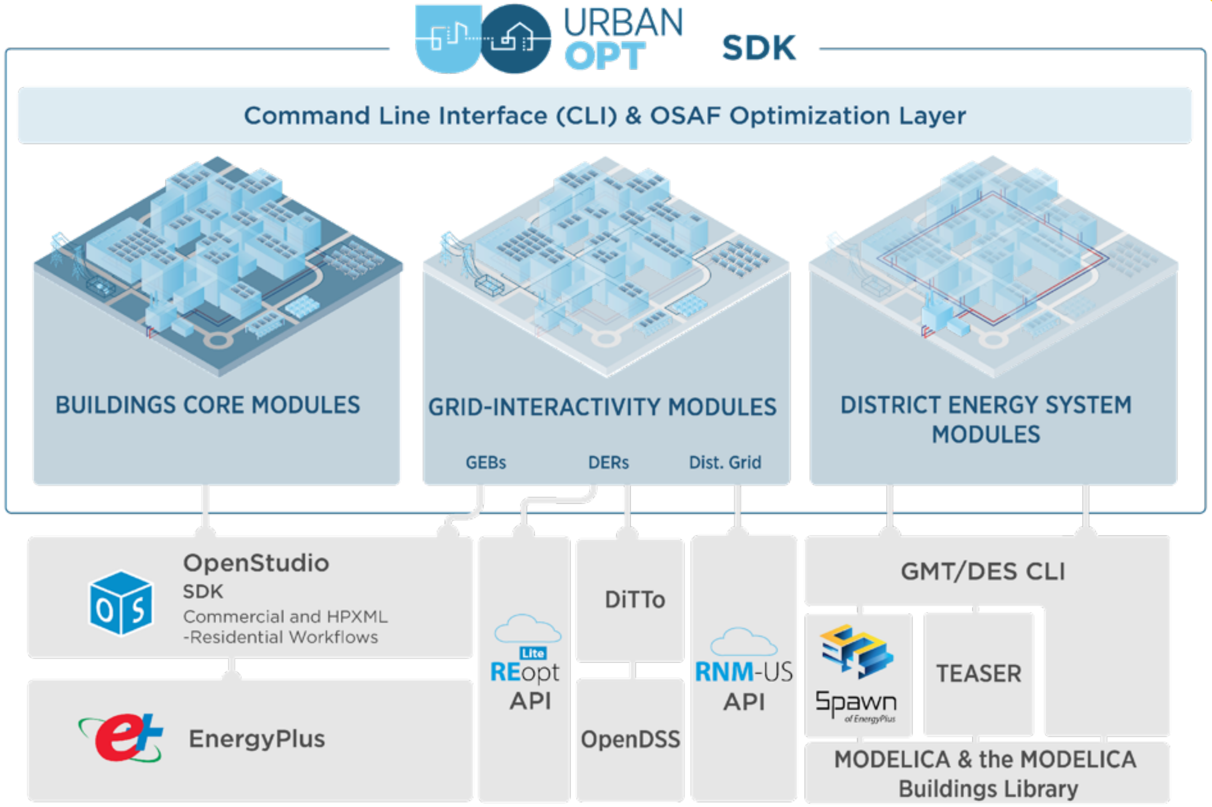
Min. Temp: 41 °F

Min. Temp: 23 °F

Source: Allen et al. (2025)

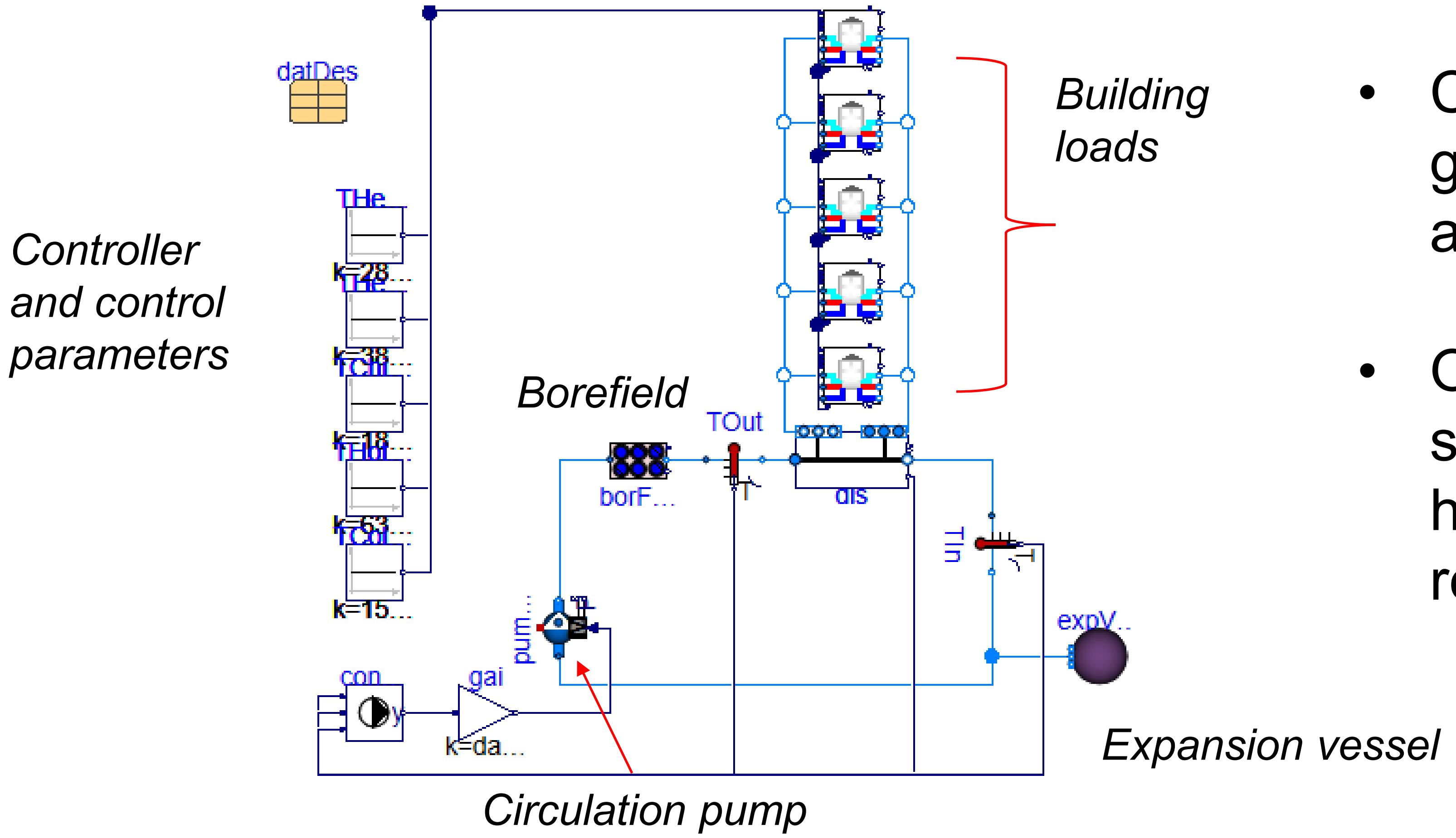
Geo-DES Modeling and Analysis

- URBANopt™ District Energy Systems (DES) is part of NREL's URBANopt analytics platform and automatically generates detailed models of geo-DES
- Building thermal loads
  - OpenStudio and EnergyPlus are well-validated energy modeling tools
- Modelica: Acausal modeling language often used for representing physical systems
  - Pressure-driven flow
  - Realistic control system architectures



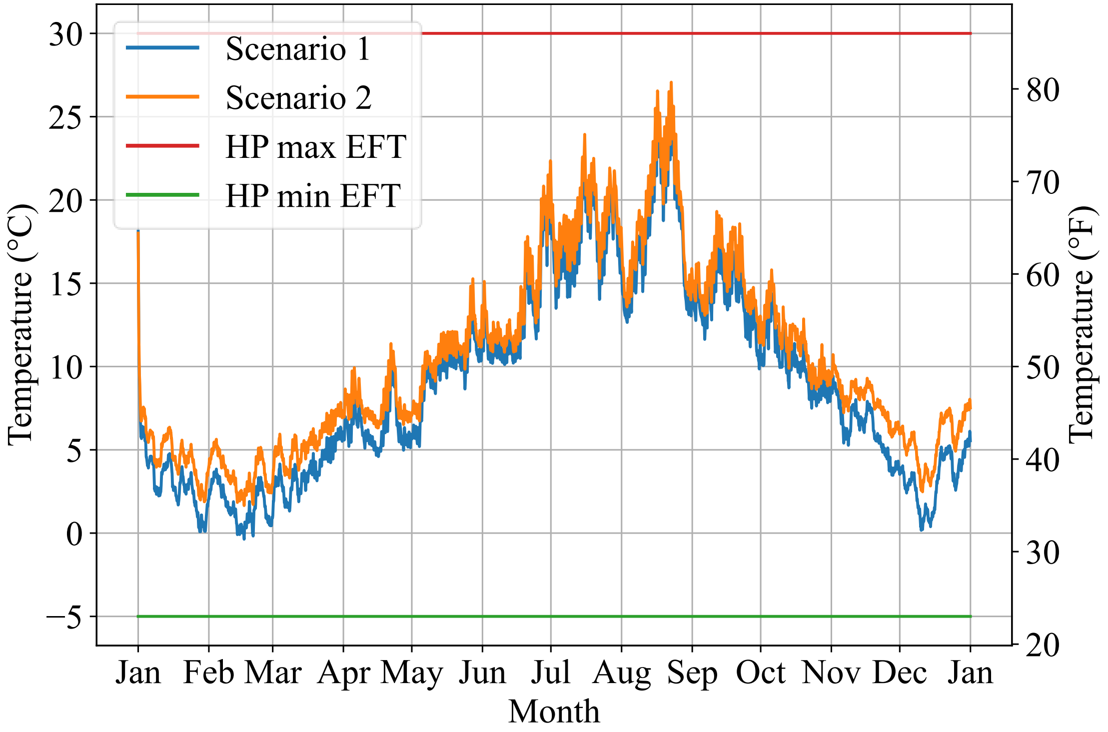
URBANopt Platform
SDK: Software development kit

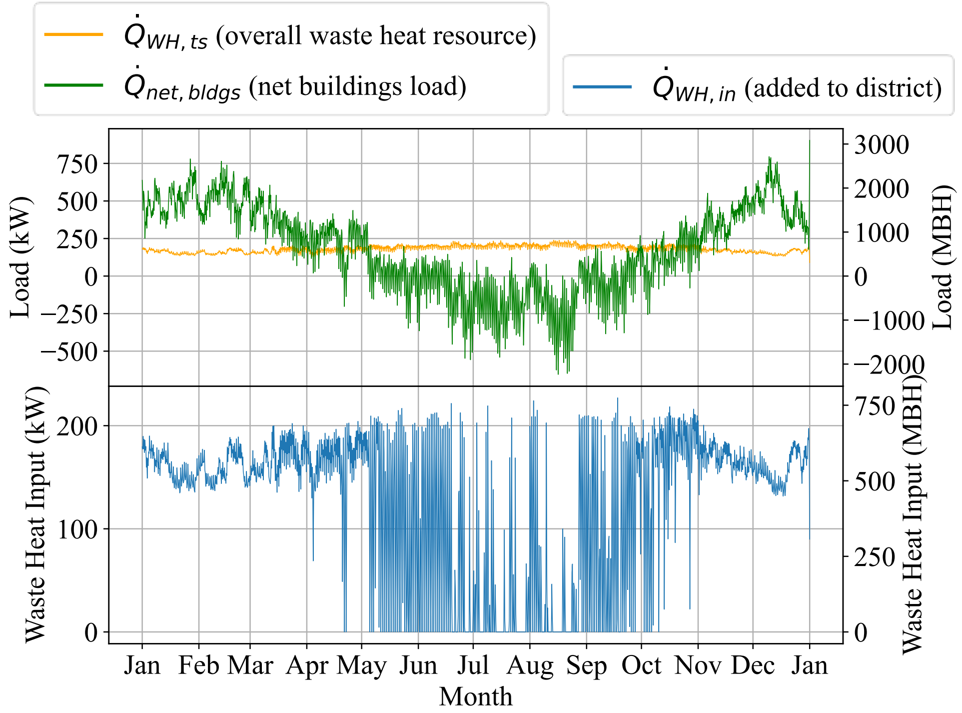
Example Geo-DES Model Layout



- Configuration of URBANopt-generated geo-DES model as shown in Dymola
- One-pipe ambient loop serving building loads, with heat drawn from and rejected to a borefield.

Example Analysis Results of Geo-DES





Analysis results from Geo-DES, with Scenario 1 corresponding to low load-side temperatures in heating, and Scenario 2, standard load-side temperatures. HP EFT: Heat pump entering fluid temperature.

Thermal Response Test Considerations

- Used to determine sub-surface properties
- Location on the site
  - Underground utilities
  - Implications from any existing soil contamination
- Duration of test
  - Several days of drilling, followed by a several-day rest period and 2-3 days to perform the TRT
- Access to water supply
- Disposal of cuttings and wastewater
- Local, state, and federal regulations

Right: Thermal response test rig (Spitler and Gehlin (2015)); Bottom: Self-propelled drilling rig installing borehole heat exchangers (https://www.geothermalindustries.com.au/)

Geo-DES Installation in Germany

Locations for pipe tie-ins to vertical wells before tie-in. Concrete “collars” are temporary.

Horizontal ground heat exchangers during installation

Tie-in of ground heat exchanger system at central plant

Photos taken during construction in November 2023

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Allen, A; Wang, J; Abdel Haleem, S; Mitchell, M; Long, N; Henze; G P; Tulley, J. (2025). “From Theory to Practice: Feasibility Study of a Thermal Microgrid at a DoD Installation.” ASHRAE Annual Conference (Phoenix, AZ).

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Spitler, J.D. and S.E.A. Gehlin. 2015. Thermal Response Testing for Ground Source Heat Pump Systems – Some History. IEA Heat Pump Centre Newsletter 33(4):29-32

Matthew Minnick, Ph.D.

Geothermal Program Manager

RESPEC

Next Generation Subsurface Thermal Energy Storage Technology and Implementation in Support of Thermal Energy Networks

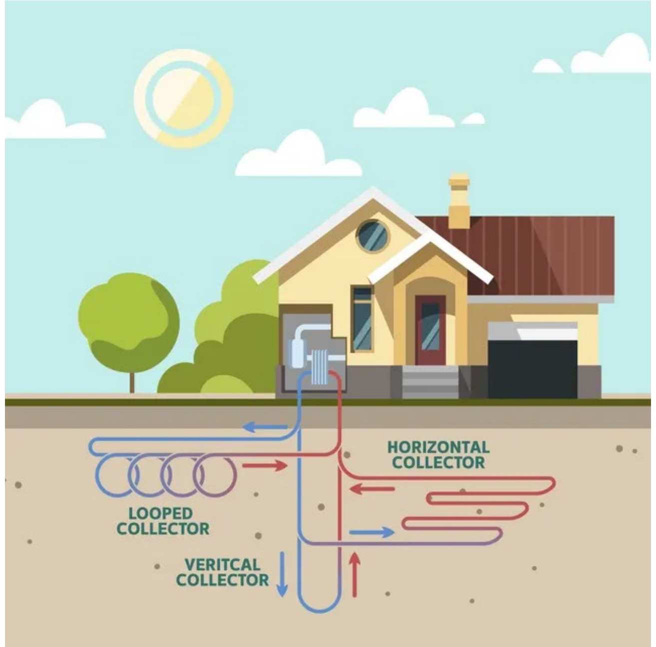
(Paradigm Shift)

Outline

- Geothermal Energy Storage
    - ATES vs BTES
    - Comparison to Traditional GHP
- Grid Amplified Building Energy Seasonal Storage (GABESS) and Thermal Energy Network (TEN)
    - Define GABESS
    - What makes GABESS different from other GEOTES
- Examples in North America and Europe
    - 1st Generation BTES Projects
    - Next Generation
- Example Next Generation Projects (JBA)
- Summary

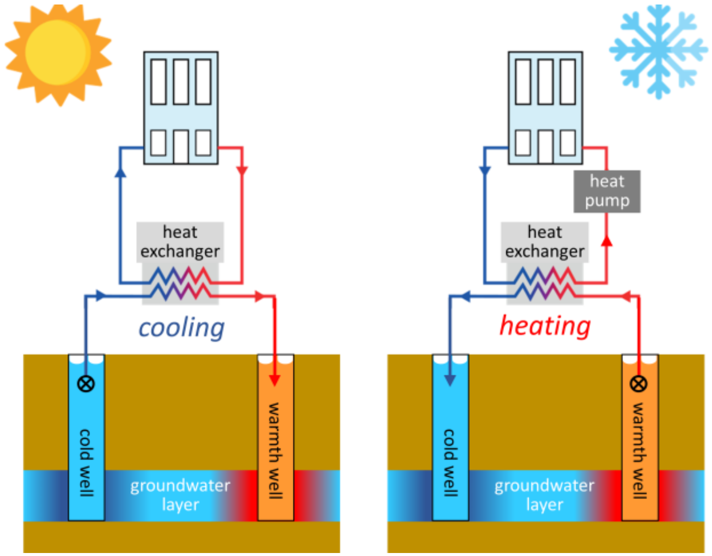
Geothermal Energy Storage (GEOTES)

Passive



https://www.thermalassociates.com/geothermal-heat-pumps

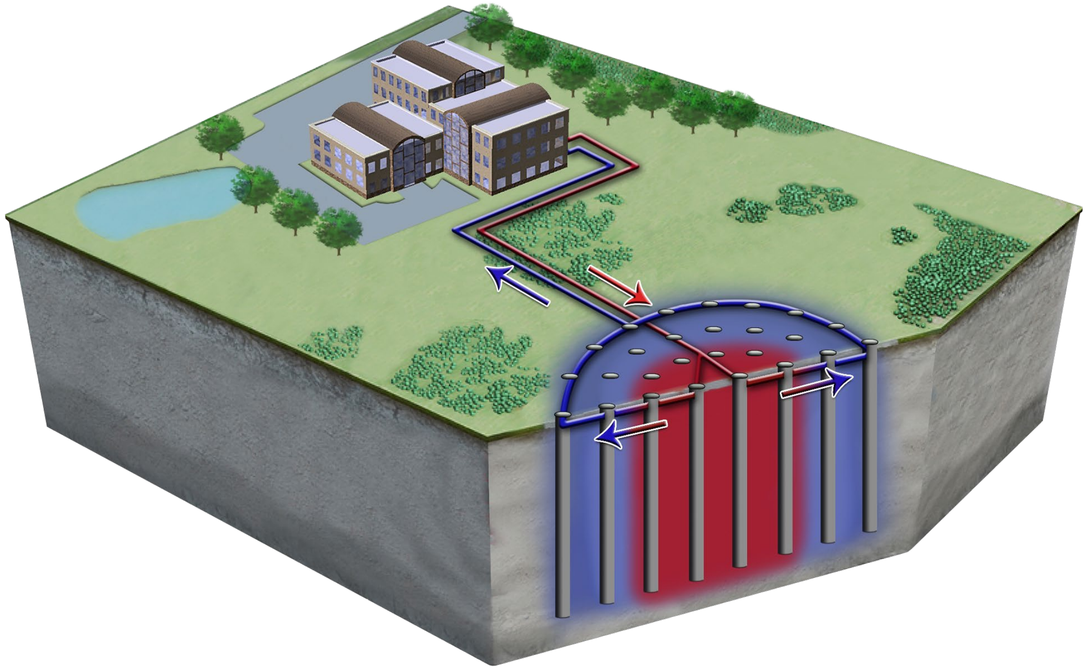
Active



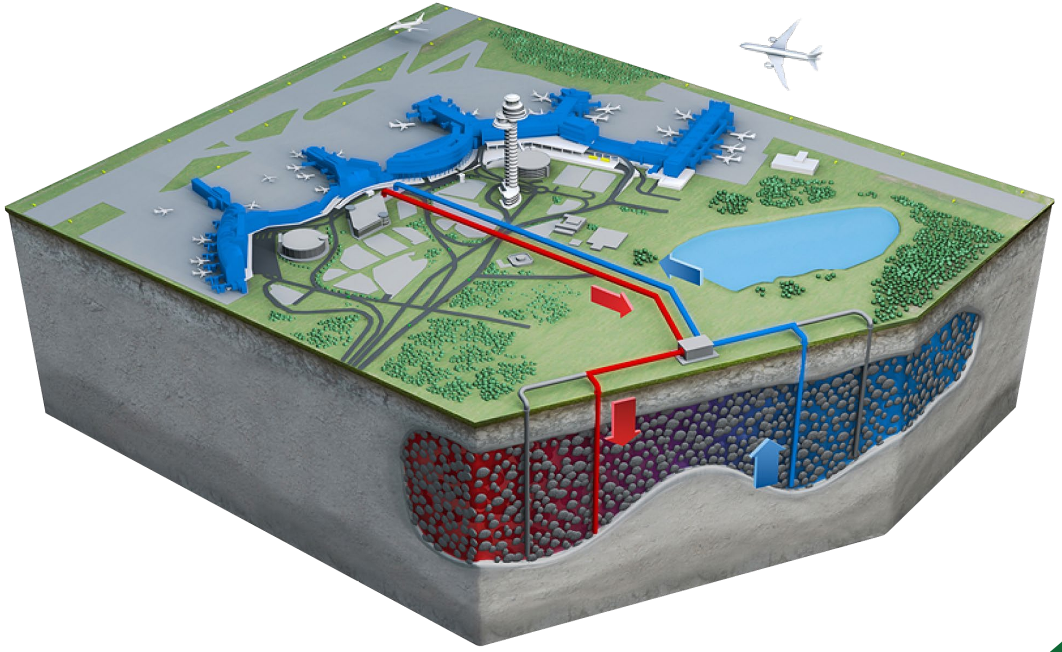
https://www.wur.nl/en/show/aquifer-thermal-energy-storage.htm

Different types of GEOTES

- Aquifer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES)



https://underground-energy.com/our-technology/btes/



https://underground-energy.com/our-technology/ates/

ATES vs BTES

	ATES	BTES
Geological Setting	Needs a Suitable Aquifer	Suitable in almost All Geologic Conditions
Environmental Permit	More complex (water law, contamination risk)	Easy to Permit (Low Impact)
Capital cost	Moderate (dependent on wells and permits)	Higher than ATES
Climate	With strong seasonal temperature difference	Suitable for all climates and Load Profiles
Storage Capacity	Higher Capacity and Efficiency per Well	More Operation Flexibility

New Concepts and Design for Next Generation System

Comparison of Old Generation vs New

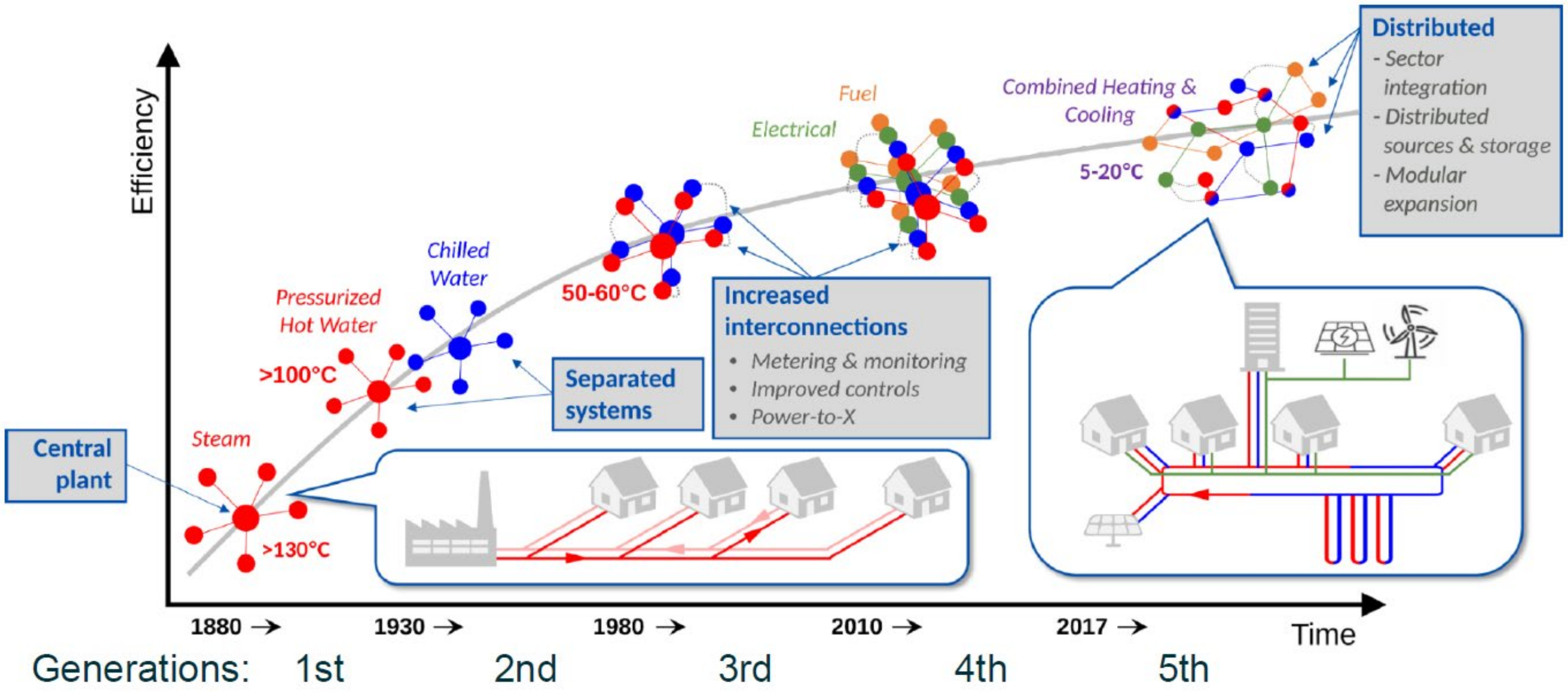


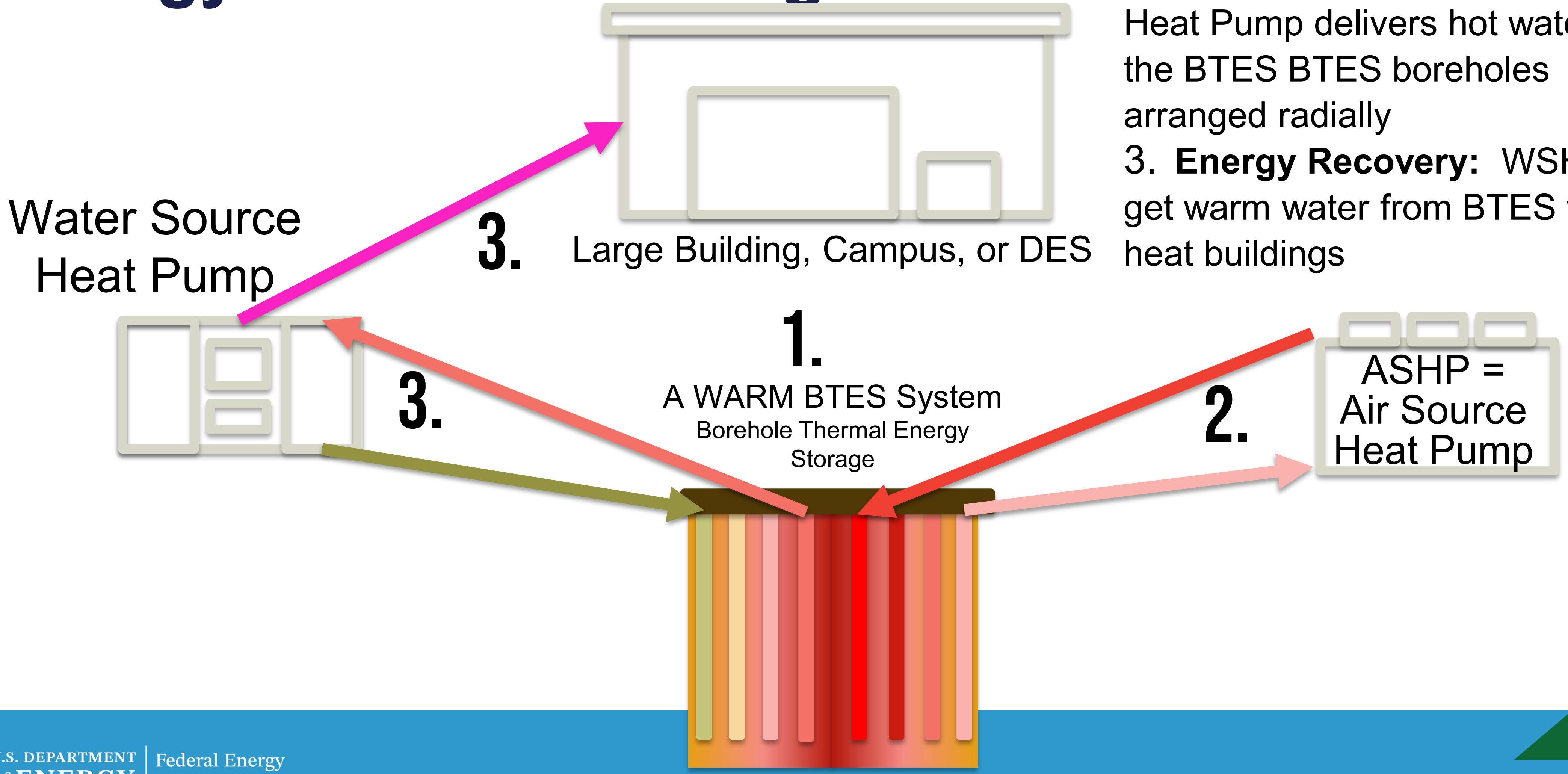
Figure: K. Hinkelman

Grid-Amplified building Energy Seasonal Storage (GABESS)

Grid-Amplified Building Energy Seasonal Storage (GABESS, pronounced “gabes”) is a combination of three proven and existing technologies in a new arrangement that delivers large grid value. The three technologies are a Borehole Thermal Energy Storage (BTES) array of geothermal boreholes, a Water Source Heat Pump (WSHP) to provide building heating/cooling thermal energy, and an Air Source Heat Pump (ASHP) to store building heating and/or cooling energy.

GABESS
Grid-Amplified Building Energy Seasonal Storage

1. A BTES is a radial arrangement of **geothermal heat pump boreholes** that stores heat in the ground.
2. **Energy Storage:** Air Source Heat Pump delivers hot water to the BTES BTES boreholes arranged radially
3. **Energy Recovery:** WSHPs get warm water from BTES to heat buildings



BTES versus Traditional Geo-Exchange System

Traditional GHP array

- All external heat transfer via ground conduction
- Large surface footprint
- Many boreholes -> large CAPEX
- Grid benefit when HVAC runs by reducing demand
- The bigger it is, the worse it performs
- A building efficiency tool

GABESS BTES array

- All external heat transfer via electric ASHPs or chillers
- Small surface footprint
- 40% to 50% reduction in CAPEX
- Same, and grid benefit when using ASHP to add energy to BTES
- The bigger the better
- Yes, but first it is a GRID cost and CO_2 tool

Advantages of GABESS

COMPARE ENERGY TECHNOLOGY OPTIONS

Geothermal Heat Pumps with Borehole Thermal Energy Storage (GHP+BTES) provides a unique combination of resiliency, cost-effectiveness, and emissions benefits for both grids and micro-grids.

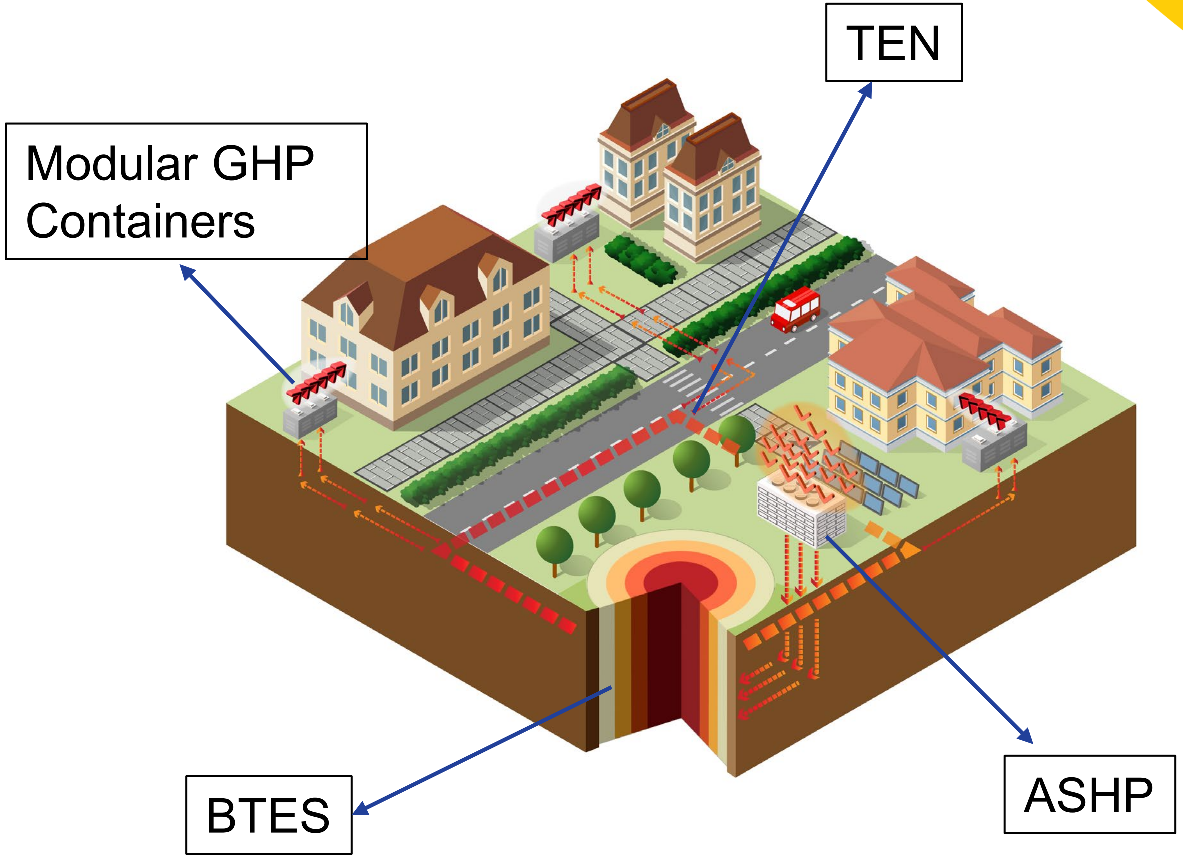
It offers a unique combination of benefits compared to other energy technology options

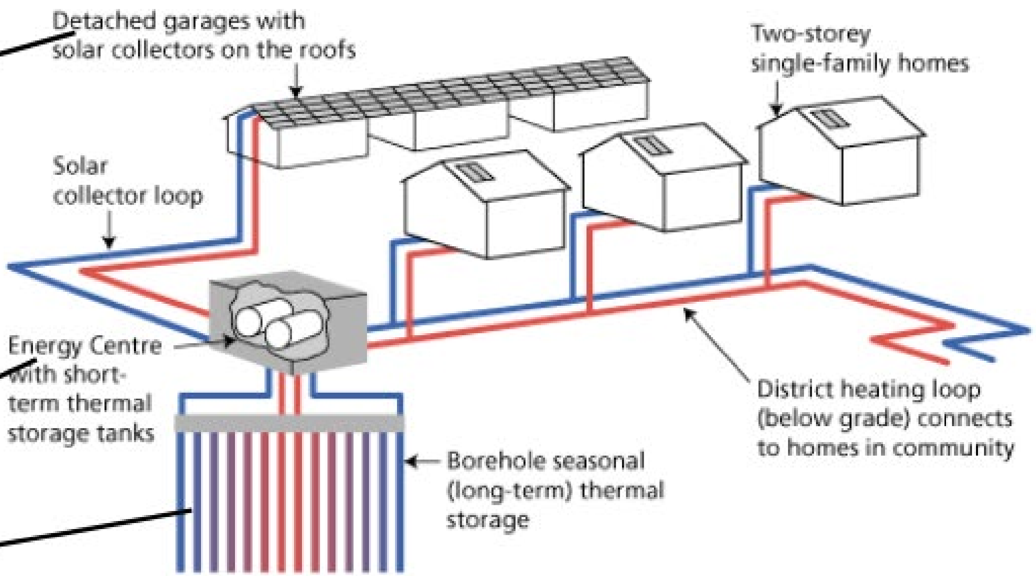
Technology Impact	GHP +BTES	Geothermal Heat Pump (GHP)	Wind/Solar (VRE)	Electro-Chemical Battery
Increase Grid Resiliency	✓	✓	✓	✓
Immune to Severe Weather Damage	✓	✓	✗	✗✓
Multi-Day Energy Storage	✓	✓	✗	✗
Reduces Grid / Microgrid Cost	✓	✓	✗	✗
Cost-Effective	✓	✗✓	✗✓	✗
Decreases Annual Total Energy Use	✓	✓	✗	✗
Low Maintenance Cost	✓	✓	✗	✗
Reduces Peak Demand	✓	✓	✗	✗
Lowers Grid & Site CO2 Emissions	✓	✓	✓	✗
The Bigger the System, the Better it Performs	✓	✗	✓	✓

Kevin Kitz @ Kitzworks

GABESS and TEN

- GABESS: Grid Amplified Building Energy Seasonal Storage
    - Air Source Heat Pumps (ASHP)
    - Borehole Thermal Energy Storage (BTES)
    - Water Source Heat Pumps (WSHP)





Solar Thermal Application-Drakes Landing, Canada "Hybrid" with above ground thermal storage & BTES

RESPEC.COM

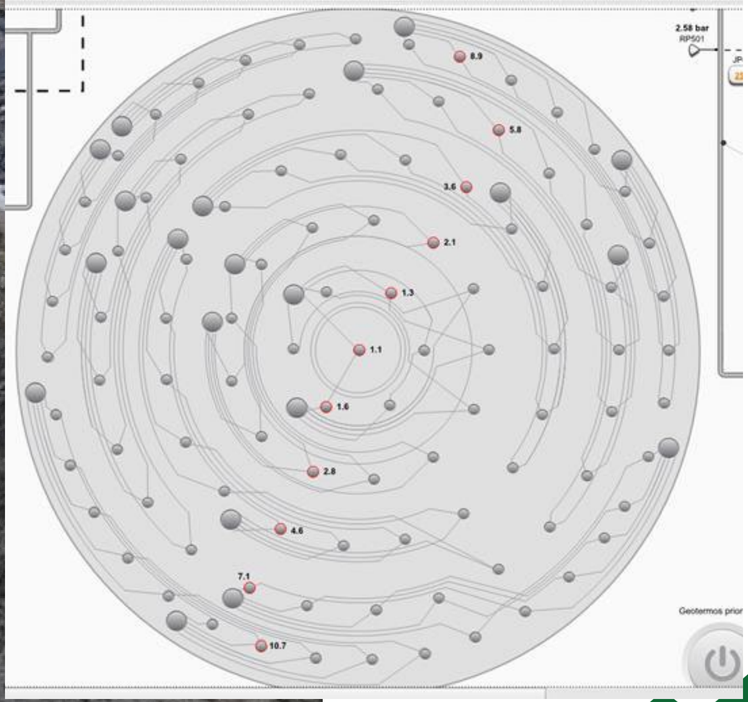
Drake Landing Solar Community, Canada

Albany GA (1st Gen BTES System)

Marine Corps Logistics Base

BTES borefield during construction

Examples in Europe (Next Gen Thinking)



BTES
Installation
Norway

Aquifer Heat Loss Crailsheim, Germany

- 80 double U-tube boreholes
- 55 m deep
- Provide heating and hot water
- Two aquifers present
- Heat loss from groundwater flow

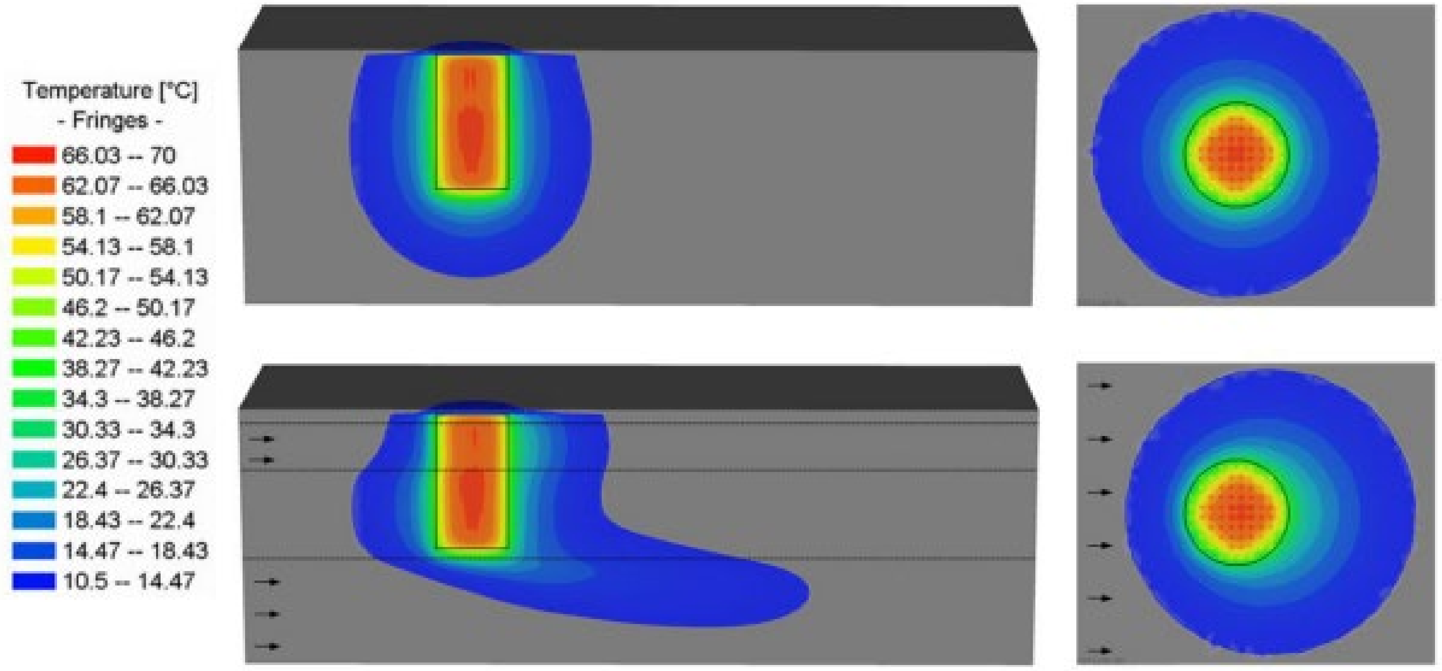


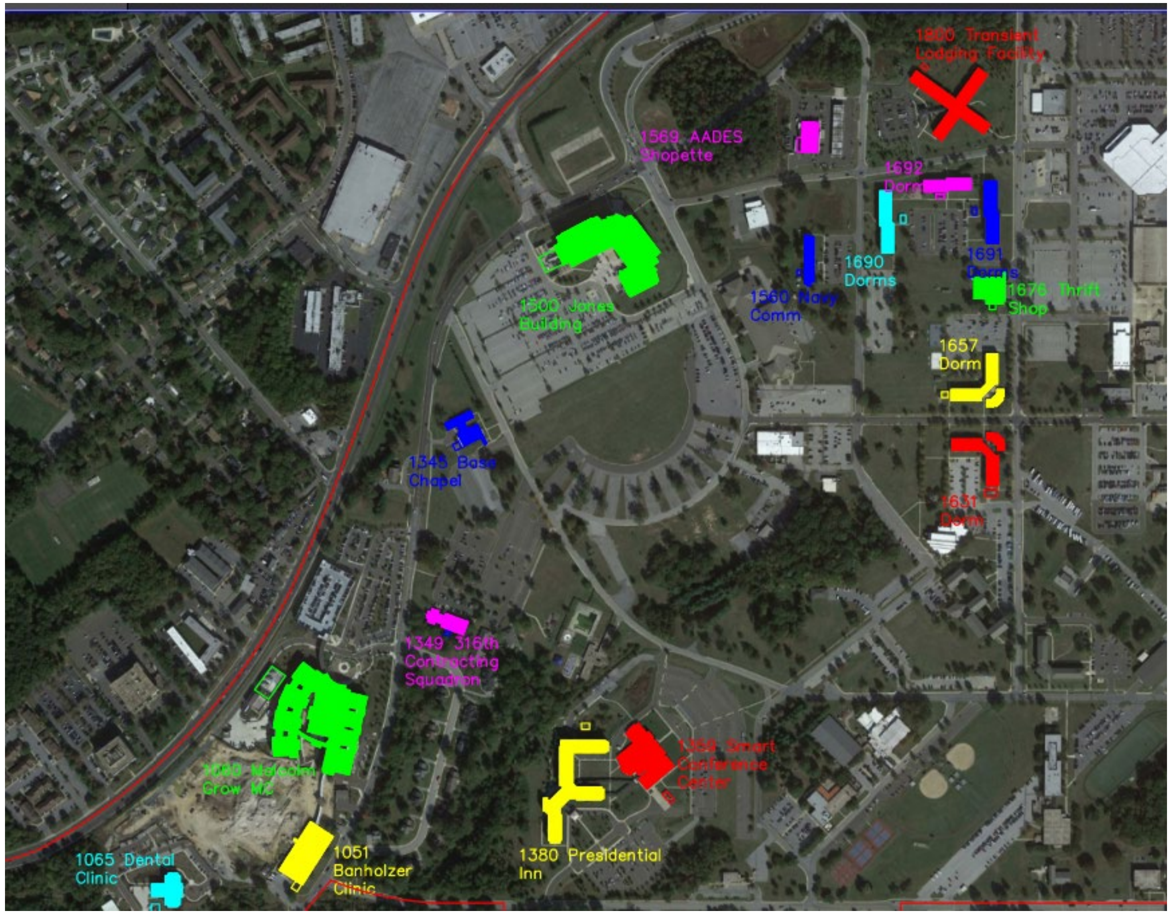
Figure 7: Simulated temperature profile of a BTES with and without moving groundwater. The horizontal cuts on the right show the temperature 15 m below ground surface (~ middle of upper aquifer)

Joint Base Andrews TEN GABESS

Description

- [ESTCP](#) demonstrates methods to help meet DoD’s energy & resilience mandates
- Grid Amplified Building Energy Seasonal Storage (GABESS)
  - Electric heat pumps and BTES
  - BTES: Borehole Thermal Energy Storage
- INF Role: Strategies for Building-Level HVAC Implementation
- Potential Widespread Application throughout DoD

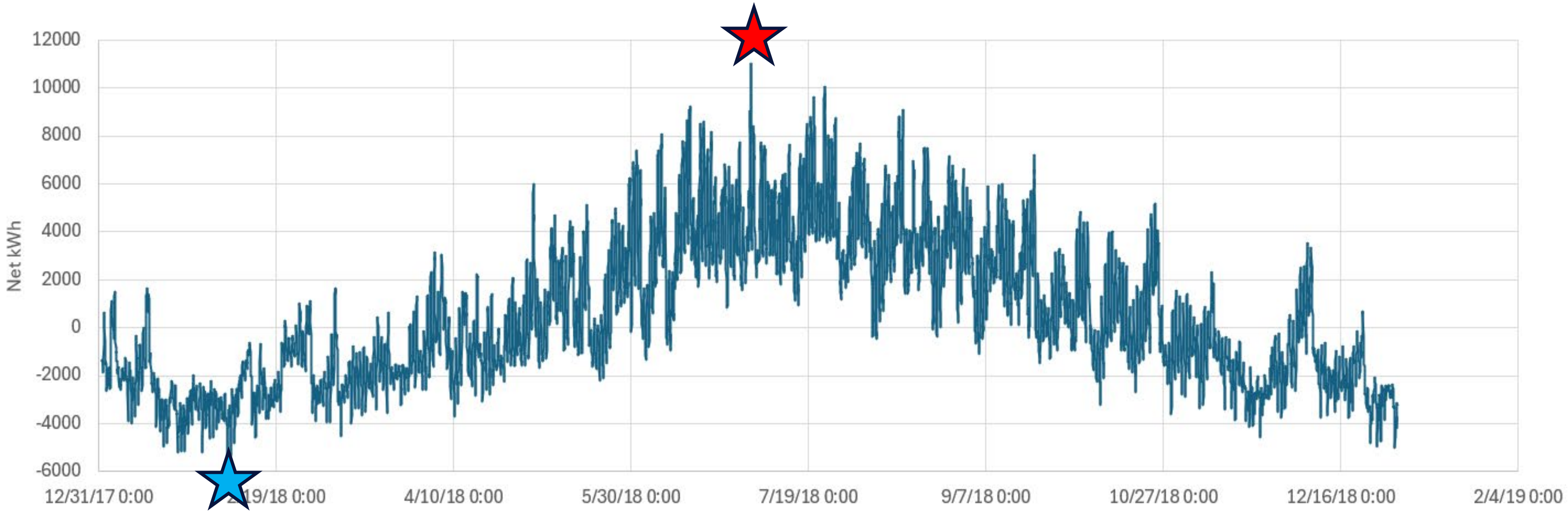
Initial project includes up to 20 buildings totaling 650,000 square feet



JBA Net energy load profile

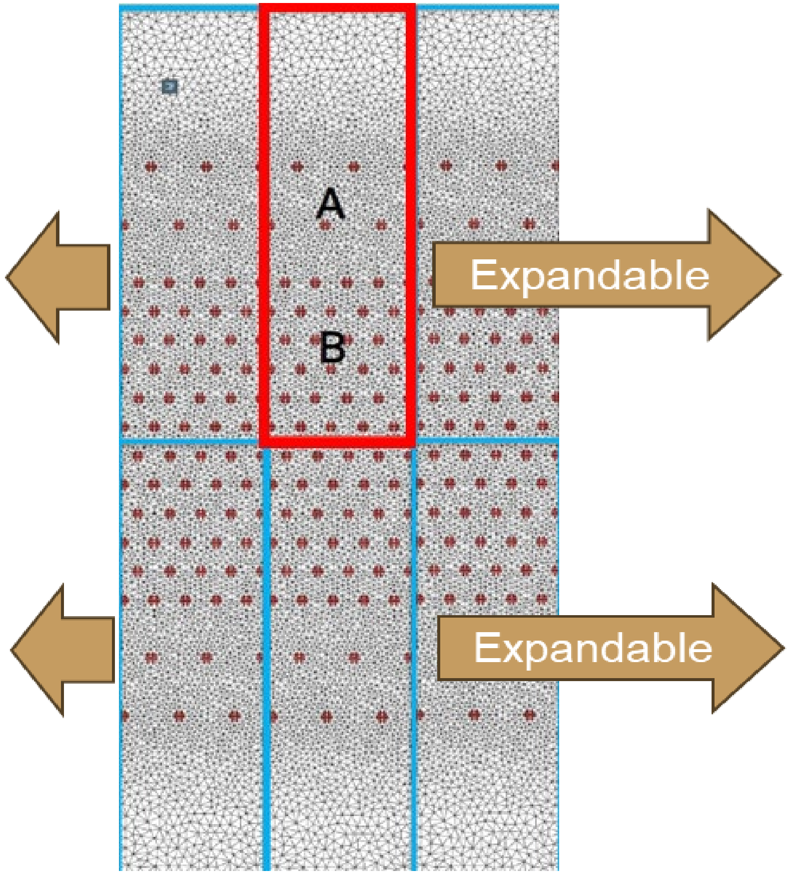
Peak net cooling load: 11,000 kWh/hr

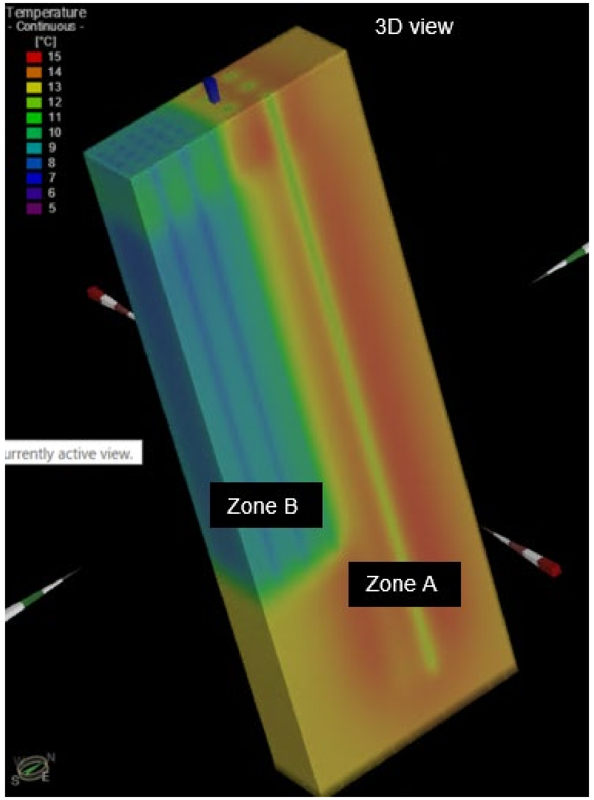
Peak net heating load: 6,000 kWh/hr



New BTES Design

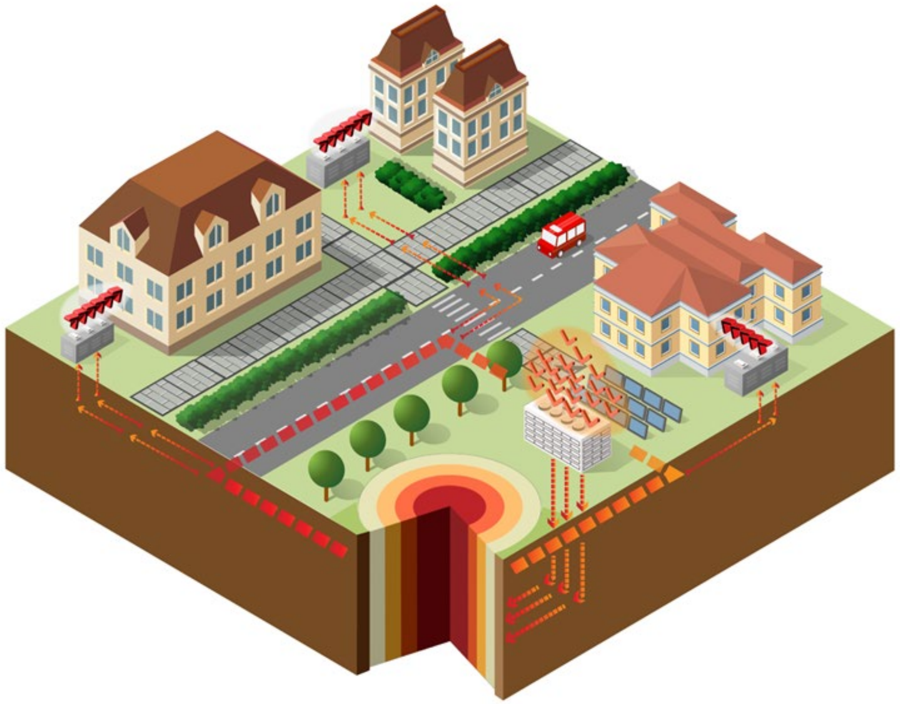
- Good For Normal Energy Network Operations
- Good For Low-temperature Storage
- Linear Fits Available Space
- Easy To Expand





Summary

- Paradigm Shift Using Existing Technology
  - Moving away from Passive GHP Systems to Active Thermal Energy Storage
  - Innovative Grid-Augmented Borehole Energy Seasonal Storage
  - Next Generation TEN-BTES



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