Design Considerations for Expanding Geothermal Networks Beyond the First Loop

- A Case Study from Framingham, Massachusetts

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ABSTRACT

This study provides an initial framework for how GEN systems can be expanded beyond the initial installation, establishing guidelines to inform future projects and accelerate the growth of the industry.

The Framingham geothermal network is growing. The design stage of the expansion ("Flagg"/Phase 2) loop in Framingham started in the fourth quarter of 2023 funded by a grant from the Department of Energy for District Heating and Cooling. The Flagg loop is designed to serve 44 additional buildings with an initially determined aggregate buildings peak heating load of ~425 tons, and has a similar order of magnitude across all parameters as those of the already operational first ("Concord"/Phase 1) loop. Design parameters were modeled using a transient system simulation program (TRNSYS) and tested for efficiency, constructability, and cost. Design choices considered include the piping interconnection method between Phase 1 and Phase 2 loops, the selection of the borefield configuration, and the design characteristics of the infrastructure hosting the borefield pumps. Additional design guidelines for the growth of GENs include a proposed definition of the line of ownership demarcation between the utility and the participating buildings, and proposed reporting measures for the size of GENs.

The results of these considerations for the Flagg loop are as follows. The butterfly connection was selected as the most efficient method to share thermal energy between Phase 1 and Phase 2 loops with minimal disruption to the already operational Phase 1 loop. Modeling of the butterfly connection shows that the two loops balance their thermal needs at the interconnection points, benefiting the overall performance of the combined Phase 1 + Phase 2 GEN system. To determine

the borehole configuration, three different borehole geometries were modeled, namely (i) traditional vertical bores with a single or double U-tube heat exchanger; (ii) vertical bores with a concentric heat exchanger; and (iii) inclined bores with single or double U-tube heat exchangers. The vertical and inclined bores with single U-tube were selected for further consideration for this project. The risks and benefits of having an underground vault versus an above-ground pump house were also considered and both were designed, with the above ground pump house selected for this site. This study also shares standard measures for reporting loads, and indicating capacity or deliverability for GENs, including defining buildings peak load (BPL) and network peak load (NPL) measures. These definitions allow for more accurate comparisons between systems to understand costs, savings, scaling benefits, and minimum viable scale for investment. Sharing the analysis of these and other design parameters, and the learnings from the Phase 1 + Phase 2 Framingham project are intended to build a referenceable body of knowledge for other GEN systems considering expansion and loop interconnection, moving this technology towards optimized replicability.

1. Introduction

Massachusetts has been a pioneer amongst other US states, in passing legislature allowing gas utilities to deploy thermal energy networks as part of their business (Bill S.2995, 2021; Bill S.2967, 2024), and the Framingham projects have been at the spear tip of this process (DPU Docket 19-120). The Framingham pilot project ("Concord"/ Phase 1) loop is the first utility-led retrofit geothermal energy network (GEN) to be built in the US. The initial Concord loop, built and operated by Eversource Gas, underwent construction from the summer of 2023 to the summer of 2024, and has been operational since then (Eversource, n.d., Bosworth et al., 2025). During construction of the Concord loop 15 utility companies from across the nation, as well as multiple other interested international delegations, visited the site to learn about this process.

Although there is increased interest from utilities to pursue geothermal energy networks (GENs), the deployment of this technology as a utility service is still in its early stages with limited standards or deployed examples on design considerations for the expansion of a GEN from the initial loop. This lack of expansion projects that could provide a reference or roadmap can increase hesitancy and caution among utilities, developers and regulators who are in a position to initiate and grow these systems. In this study we present the main engineering design considerations for the expansion loop of the Framingham GEN system, with a second distribution ("Flagg"/Phase 2) loop connecting to the existing operational distribution ("Concord"/ Phase 1) loop.

The design stage of the Phase 2 loop in Framingham started in the fourth quarter of 2023, funded by an initial award from the Department of Energy for District Heating and Cooling (Office of Geothermal, n.d.), and the project was then selected for a construction award that launched in late 2025. The construction drawings were finalized in 2026 with a tentative construction start date of Spring 2027 pending regulatory approval.

As designed, the Flagg loop has the capacity to serve 44 buildings, including 13 apartment buildings from the Framingham Housing Authority (FHA); 30 single and multi-family homes; and a public school as shown in Figure 1a. Together, the Flagg and Concord loops, also referred to as Phase 2 and Phase 1, respectively, form the Framingham Geothermal Energy Network (GEN). The Framingham GEN is a first of its kind globally, in that it is a single pipe ambient thermal network owned and operated by a utility (Eversource Gas) with an already operational loop and construction plans for an expansion loop. The Flagg loop therefore presents several novel design considerations in the context of the expansion of geothermal networks beyond the initial distribution loop.

This study uses the definition of GENs provided by Magavi et al. (2024), where the GENs system has three main components, the thermal resources or boreholes, the distribution networks or main loop, and the end-user including the building infrastructure components. The work presented focuses on several major engineering design components and considerations related to the thermal resources and the distribution loop.

This paper is organized in nine sections that discuss the following topics: ii) modeling of borefield configurations; iii) proposed method for standardizing reporting of GEN system loads and capacity; iv) interconnection options between GEN distribution loops; v) combined thermal modelling of Phase 1 and Phase 2 loops; vi) preemptive planning for potential future expansion beyond Phase 2; vii) infrastructure ownership demarcation between utilities and customers; viii) considerations between below ground and above ground vault designs, and ix) conclusions. Details in these sections describe many of the factors influencing decision-making and may provide a point of reference for comparable GEN projects in the future.

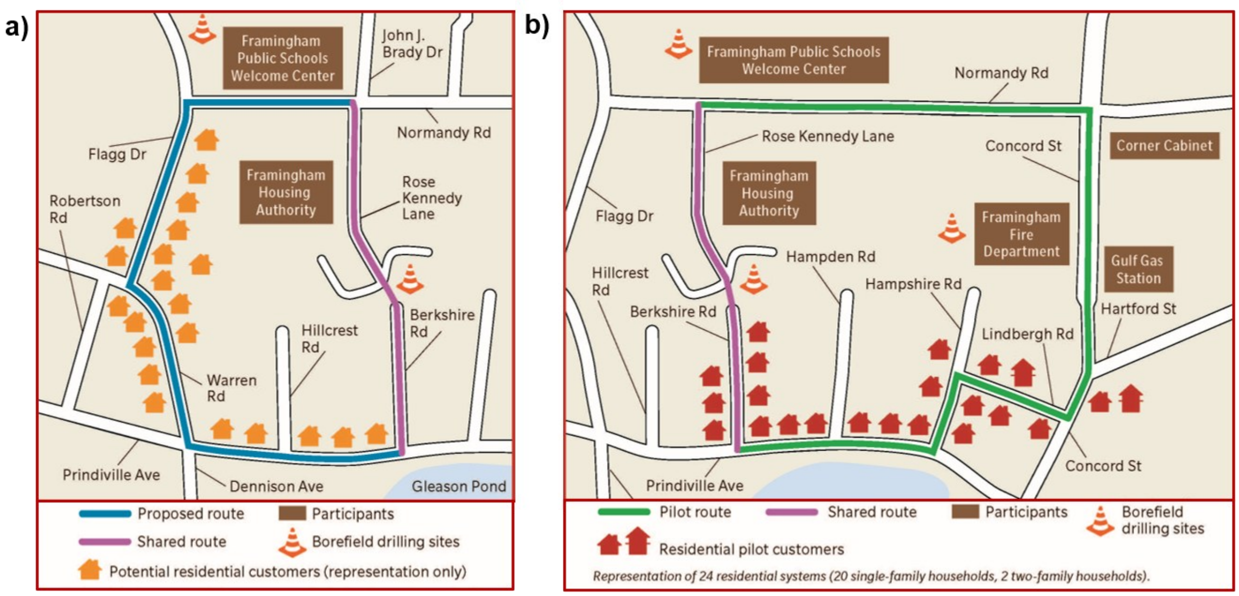


Figure 1: A map sketch of the Framingham geothermal energy network (GEN) system. a) Flagg or Phase 2 GEN. b) Concord or Phase 1 GEN. Figure modified from Eversource (n.d)

2. Borefield Design

In designing the single borefield required for the Flagg loop expansion project, the design team evaluated 3 types of boreholes: traditional vertical boreholes, inclined boreholes, and vertical concentric boreholes. The borehole designs were evaluated for performance, constructability and cost. The objective of this analysis was to develop the best strategy to reduce the footprint and cost of the geothermal borefield, while maintaining operation and capacity of the connected Phase 1 or Concord loop. Multiple site factors influenced the modeling of the Flagg loop borefield configurations, including consideration for the numerous (56) trees and proximity to a Concord loop borefield. These characteristics require an optimized design of bore surface locations and trajectories to minimize site impact and costs. The borefield configurations evaluated are described in the next section.

2.1 Borefield Configurations Modeled

All borefield configurations modelled, all bores were prescribed a length of 850 feet. While the borefield layout and borehole count used in the Flagg Loop will be further refined based on site conditions, the configurations modeled are used to compare different scenarios and estimate the efficacy of each configuration.

2.1.1. Vertical Bores (Traditional Drilling)

This scenario models a traditional geothermal field consisting of vertically drilled bores, typically spaced uniformly, extending to a consistent depth, and containing a U-tube pipe surrounded by grout within each borehole. This approach represents the most common and well-established method for geothermal heat exchange systems, with a long history of deployment and predictable performance characteristics. The vertical bores are distributed in a grid pattern with 20 ft spacing on center, as depicted in Figure 2a. While these bores were modelled using both, a single and double U-tube as the ground heat exchanger, the single U-tube with this borefield configuration, is considered the Basis of Design (BOD) for comparison with the other borefield scenarios.

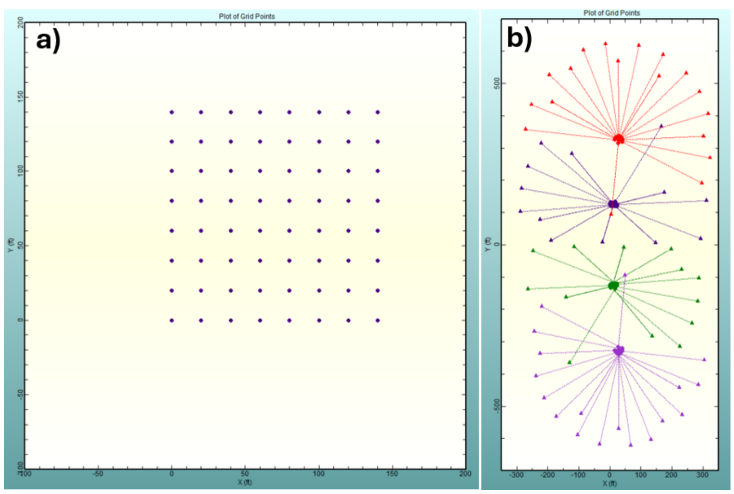


Figure 2: Borefield configuration geometries. a) Layout representing vertical bores Basis of Design (BOD) with 20 ft spacing on center. The concentric bores have this same configuration. b) Inclined bores for Scenario B, distributed amongst four platforms, with 18, 13, 13 and 18 bores on each platform from North to South respectively.

2.1.2 Inclined Bores

Inclined bores refers to the inclined drilling of bores, where bores are spaced tighter together at the surface and angled out up to 25° from vertical, so the spacing between bores increases with depth. The main advantage of this drilling methodology is to reduce the impacted surface area. Several configurations of inclined boreholes were considered, with a focus on bores drilled from a central platform ‘nodes’ or ‘clusters’ in order to minimize the impacted surface area. The modeling of the inclined bores can be grouped into two scenarios, referred to as A and B. In scenario A, the inclined bores were modeled in grids of 64 bores with 5, 10, 15, and 20 ft spacing at the surface, as depicted in Figure 3a, 3b, 3c and 3d respectively. The central bores in these grids were vertical with deviation increasing with distance from center. The perimeter bores reach a maximum angle of 20° as shown in Figure 3. In scenario B the inclined bores were modeled as drilled from 4 different platforms with 2.5 ft spacing between bores, and each platform containing: 18, 13, 13, and 18 bores at varying angles up to 20° as shown in Figure 2b. Scenario B was designed to mimic a Phase 1 borefield layout on Normandy Road that used inclined drilling. In both scenarios A and B the inclined bores were modeled with single and double U-tubes.

<u>2.1.3 Concentric Tube (Tube-in-tube GHX)</u>

The heat exchanger in these concentric bores differs from traditional vertical bores with U-tube pipes by utilizing concentric tubes in which fluid is sent down the bore through a wider outer tube and the fluid returns back up the bore through a narrower inner tube. This method creates turbulent flow in the outer tube and increases surface area of exchange, increasing heat transfer. These bores are also drilled vertically and typically spaced uniformly and extending to a consistent depth. Similar to the traditional vertical bores, concentric bores were modeled in a grid with 20 ft spacing on center as shown in Figure 2a.

Borefield configuration performance for all the scenarios (vertical bores, inclined bores and concentric tube) was modeled hourly over a three-year simulation period for the given site using Ground Loop Design (GLD) software.

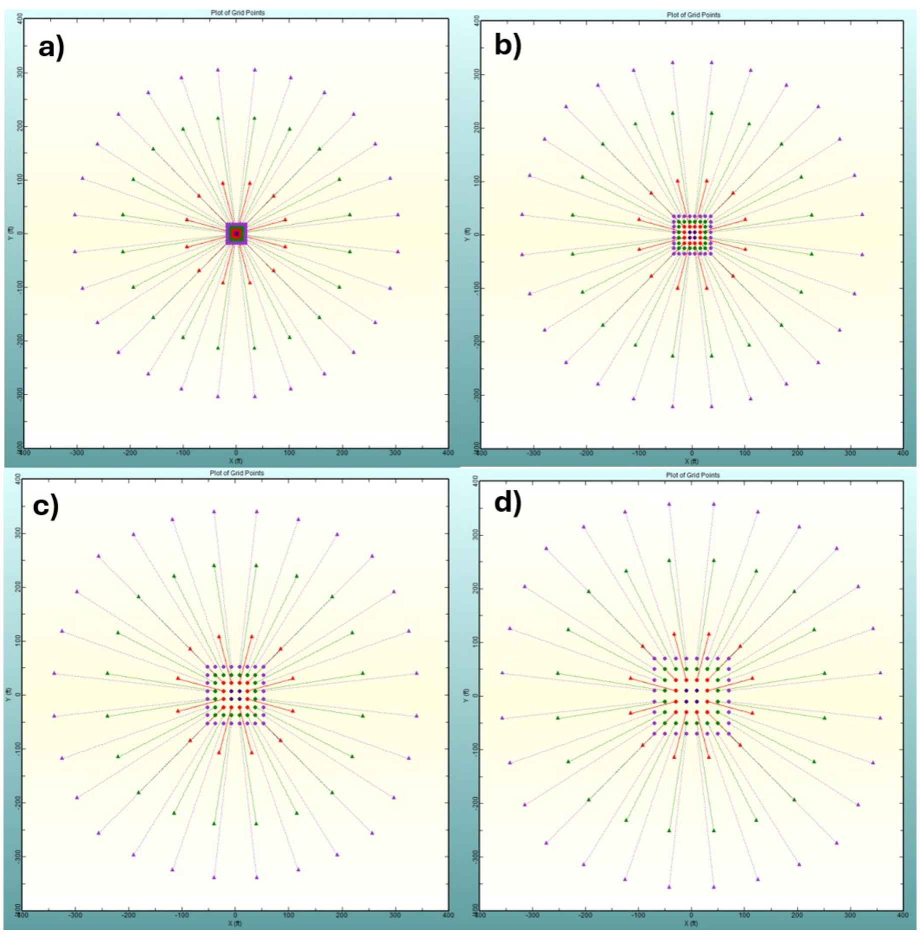


Figure 3: Inclined bores square grid arrangement for Scenario A, with 5 ft, 10 ft, 15 ft and 20 ft spacing for a), b), c) and d) respectively.

2.2 Borefield Configurations and Modeling Software Comparison

Additional modeling of inclined bores was done to compare different arrangements and different modeling softwares. Ground Loop Design (GLD), Transient System Simulation tool (TRNSYS), and COMSOL were used. GLD calculates heat pump entering water temperature (EWT) and leaving water temperature (LWT) by using G-functions, which are thermal response functions. GLD is driven by loads and assumes a constant GPM/ton flow rate. COMSOL and TRNSYS both use a node mesh through the soil and calculate the nodal soil temperature throughout the ground and the heat transfer between nodes. These softwares also include thermal response functions, but at a more detailed scale than GLD. The COMSOL and TRNSYS models for this analysis are driven by flow rate and ground EWT profiles. Calculations in GLD are quick and useful for sizing simple geothermal systems (not connected to an ambient loop or a central plant with other thermal assets), whereas COMSOL and TRNSYS are computationally and time intensive to simulate but have more modeling options. COMSOL has capabilities to model detailed soil layers, complicated borefield layouts, and the effects of aquifers and groundwater movement. TRNSYS has capabilities to model geothermal systems with complex networks or interactions with other thermal assets. For this analysis, two different GHX component models were used in TRNSYS: the first, referred to as Type A, represents a detailed ground coupling model where the soil nodes and pipes are manually specified in a rectilinear coordinate system, so inclined bores can be modeled piecewise. The second model, referred to as Type B, is a proprietary vertical borefield model in which inclined bores are modeled using an equivalent spacing.

The different borefield configuration arrangements modeled with different softwares were: i) vertical bores 8x8 square; ii) vertical 2x32 lines; iii) inclined 8x8 square (Figure 4); and iv) inclined 2x32 linear **(**Figure 5**)**. The vertical arrangements used 20 ft spacing, and the inclined arrangements used 5 ft spacing at the surface and 20° maximum angle from vertical. For this part of the analysis, all arrangements used bore lengths of 804 ft (245 m) and all models were simulated hourly over a three-year time period.

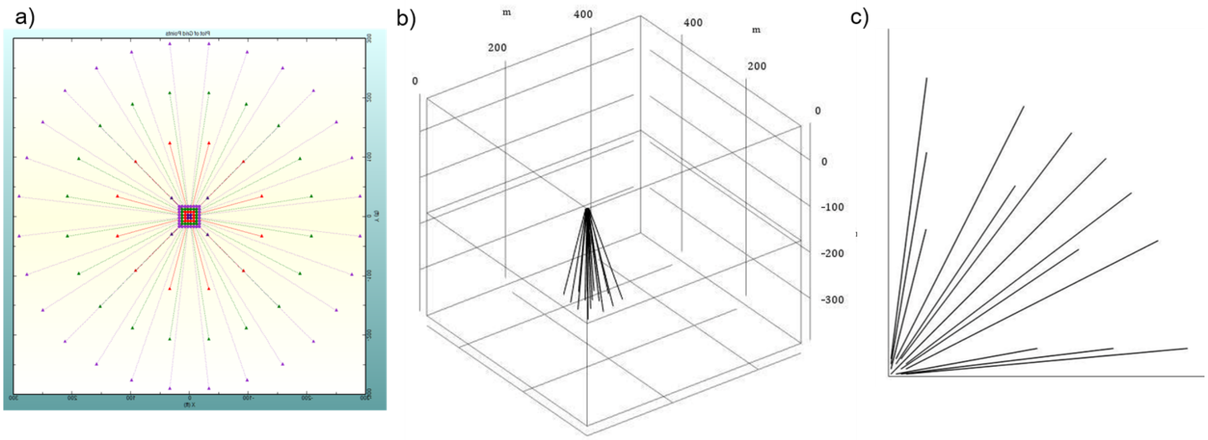


Figure 4. Inclined bores arrangement for 8x8 square grid with 5 ft spacing on surface. a) aerial view, b) 3D view, and c) detail view of northeast quadrant of borefield layout.

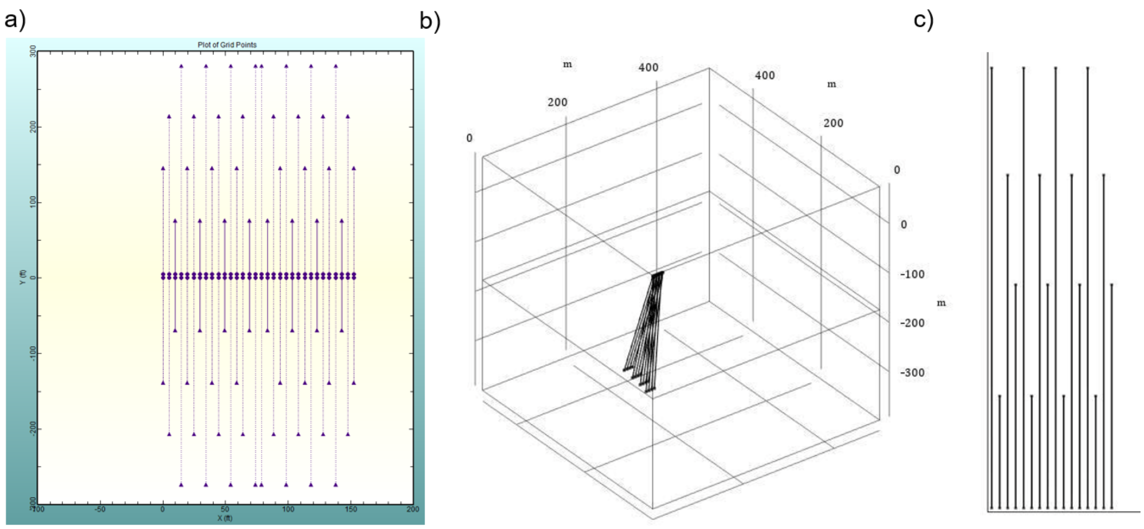


Figure 5. Inclined bores arrangement for 2x32 square grid with 5 ft spacing on surface. a) aerial view, b) 3D view, and c) detail view of northeast quadrant of borefield layout.

2.3 Borefield Configuration Results

2.3.1 Results on Borefield Configurations Modeled

For borefields, or ground heat exchangers (GHX), better performance is characterized here as warmer leaving water temperatures (LWT) in winter, when heat pumps take heat from the ground, and cooler LWT in summer, when heat pumps reject heat to the ground. The heat pumps will be able to operate more efficiently with warmer temperatures in winter and cooler temperatures in summer. A better performing GHX may also be indicative that the GHX size can be reduced. Therefore, this analysis primarily used the GHX LWTs to compare the effectiveness of the different borefield configurations.

For inclined bores, performance was quantified by comparing the GHX LWT for the different inclined bores configurations. The minimum LWT in winter and maximum LWT in summer for all scenarios tested are listed in Table 1. For these borefield performance results, the minimum LWT in winter is the driving factor because the winter temperatures are closer to the design conditions (heat pump limits) than the summer temperatures. In this analysis the heat pump design limits used are minimum ~35°F and maximum ~90°F entering water temperatures. With these limits, a maximum GHX LWT in the 70s°F indicates that the borefields have more unused cooling capacity. Similarly, a minimum GHX LWT between 36°F to 40°F indicates that the borefields are limited and sized for heating mode. This occurs when the loads on the GHX are heating dominant, meaning that the buildings absorb more heat from the ground in winter than they reject to the ground in summer.

The differences between the minimum LWTs for the inclined 10-20 ft spacing are within the noise of the modeling simulation as depicted in Table 1. The double U-tubes resulted in performance improvements over the single U-tubes. However, for this site, the increase in performance is not large enough to justify the additional cost and drilling difficulty to install double U-tubes. The inclined 5 ft spacing and vertical 20 ft spacing had nearly identical LWTs (for both single and double U-tubes), indicating a comparable performance between the two. While increasing the spacing for the inclined arrangements generally results in better performance, realistically inclined with spacing greater than 5 ft would not be constructed because the borefields are no longer significantly reducing the surface area footprint over a vertical arrangement, which is the primary reason for using inclined bores at a drilling cost premium.

Table 1. Borefield leaving water temperature (LWT) extremes for the different borefield configurations. Better effectiveness is achieved when LWT is cooler in the summer and warmer in the winter.

Spacing at Surface (ft)	Angle	Layout	U-tubes	Min LWT in Winter (F)	Max LWT in Summer (F)
2.5	Inclined	Clusters	Double	39.32	70.85
5	Inclined	Square	Double	38.5	70.79
10	Inclined	Square	Double	39.66	70.07
15	Inclined	Square	Double	40.01	70.33
20	Inclined	Square	Double	39.81	70.51
20	Vertical	Square	Double	38.42	71.3
5	Inclined	Square	Single	36.1	74.07
10	Inclined	Square	Single	37.43	73.56
15	Inclined	Square	Single	37.77	73.82
20	Inclined	Square	Single	37.57	74
20	Vertical	Square	Single	36.15	74.77

The Scenario B clusters layout method performed better than the Scenario A 5 ft spacing inclined double U-tube and comparable to the 10-20 ft spacing inclined double U-tube as listed in Table 1. The clusters layout method uses a smaller surface area for drilling compared to the vertical bores while overall using a larger subsurface area for thermal exchange. However, the clusters layout analyzed has four drilling areas and each one of these needs to account for equipment mobilization, using a larger surface area. When accounting for this, the clusters scenario results in a similar impact on the number of trees needed to be removed when compared to the BOD. Because of this, this layout of the clusters method did not meet the outcomes for prioritized implementation in this project.

For concentric tube bores, performance was quantified by comparing the concentric tube borefield size needed to reach the same LWT design conditions as the BOD 64 vertical bores. The modeling results showed that concentric tube bores only outperform traditional vertical bores at high flow rates, which occur mainly during peak heating and cooling periods. Since the peak conditions are the key points for sizing borefields, this leads to a smaller number of concentric tube bores required compared to traditional bores. The modeling results indicated that 55 concentric tube bores could be used instead of 64 traditional bores, which is a 14% reduction in number of bores, resulting in a 16% reduction in surface area used for drilling.

High-level costs were estimated from the design development phase to compare the different borefield configurations. Although concentric tube bores have higher performance, they cost significantly more per bore to drill and install. This study concluded that while their better performance with high flow rates could allow for a reduction in the number of bores required, the reduction for this project is not significant enough to result in cost savings over the BOD.

Surface area impacted by the borefield is a key design consideration. Inclined bores use less surface area than the vertical bores or the BOD. Nevertheless, contrary to our initial expectations, the modeling results for the Flagg loop location and design do not show significant performance improvement of the inclined bores over the BOD, resulting in the same number of bores estimated for both options. In order to account for the value of surface area reduction of the borefield options, a minimum cost of surface area remediation (landscaping) was included in the analysis, as listed in Table 2. The cost for inclined bores is estimated to be higher than the BOD when accounting for drilling, loop installation, and mobilization, but could be slightly less after accounting surface area remediation. It is possible that the surface area reduction of the inclined bores has additional value aside from the monetary amount for surface area remediation – for example, if having more unimpacted surface area leaves space for additional infrastructure or if it is more aligned with stakeholder preferences such as preservation of tree canopy. The bore counts and costs presented in this section are for comparison purposes only between borefield configurations and are not representative of the final bore counts and costs.

Table 2: Comparison of borefield configurations, including vertical bores (BOD), inclined bores, and concentric bores.

Parameter	Units	BOD	Inclined	Concentric Tube
Number of bores	bores	64	64	55
Surface area estimate	ft^2	19,600	Drilled area: 300 Total affected area: 26,949	16,384
Surface area percent of BOD	%	100%	Drilled area: 2% Total affected area: 137%	84%
Surface area remediation	$\$4/ft^2$	78,400	1,800	65,536

2.3.2 Results on Borefield Configurations and Software Comparison

The LWT results for the comparison between different modeling softwares and different borefield configurations are shown in Table 3. The results from this analysis indicate that the bore patterns modelled did not have a significant impact on the results, indicating that the bore pattern can be determined by other design criteria such as available space, site coordination, stakeholder input, and costs rather than energy effectiveness. Additionally, the modeling results demonstrate that borefield sizing will be similar between vertical and inclined arrangements. The comparison between modeling software from Table 3 shows that GLD provided significantly different results from COMSOL and TRNSYS, with consistently lower LWT in the winter and higher LWT in the summer. However, it is reassuring to the authors that the modeling tools that are built to account for more complex scenarios (COMSOL and the two TRNSYS models) present similar LWTs for the different borefield configurations. Determining the specific factors driving the difference is a topic for further inquiry.

Given the borefield modeling results, which show that the inclined bores have a similar performance to the BOD, at the time of writing this paper, both options are being considered for this project. The inclined bores with the 2x32 square grid and 5 ft spacing on surface were selected amongst the different inclined bore configurations, as they have a similar performance to the other scenarios and can more easily adapt to the site conditions including the proximity of the adjacent borefield from Phase 1. Additionally, this inclined configuration has a surface geometry that is more accessible to the drilling technology used more widely by geothermal drillers. By contrast, the surface configuration of the inclined clusters or the inclined square formation could pose additional challenges to drilling organizations potentially reducing the number of bidders.

Table 3 Borefield configurations and software comparisons. Larger leaving water temperature (LWT) in winter denotes a better performance. Similarly, lower LWT in summer denotes a better performance.

Borefield Configuration	Model	Winter Min LWT (°F)	Summer Max LWT (°F)
VERTICAL - 8x8 square	GLD	37.74	76.42
	COMSOL	42.00	70.95
	TRNSYS-A	41.52	70.82
	TRNSYS-B	41.41	70.87
VERTICAL - 2x32 lines	GLD	38.03	76.42
	COMSOL	41.74	72.13
	TRNSYS-A	41.45	70.93
	TRNSYS-B	41.37	70.88
INCLINED - Square Formation	GLD	37.61	74.39
	COMSOL	42.47	70.16
	TRNSYS-A	41.10	71.67
	TRNSYS-B	41.42	71.15
INCLINED - Linear Formation	GLD	34.66	77.48
	COMSOL	42.91	68.99
	TRNSYS-A	41.18	71.40
	TRNSYS-B	41.42	71.22

3. Reporting GEN System Size

This section first defines proposed measures for communicating the size of geothermal networks and then applies those measures to the Framingham GEN system to allow for systematic comparisons.

3.1 Introducing System Measures for Thermal Energy Networks

There is a lack of consistency in describing the system size of GENs throughout the industry. In contrast to other energy systems, where the determination of system loads, capacity and deliverability is well defined, there are currently multiple ways to report such measures for a GEN, and often the method used is not stated. The ambiguity arises in part from the bidirectional nature of the single pipe GEN system with its provision of both heating and cooling services. To reach the consistency needed, this study proposes using the *building loads* and *network loads* GENs system size measures, as defined by HEET (2026), for both heating and cooling.

The first set of *building loads* measures are necessary to mirror other technologies for comparison and are straightforward to calculate without any advanced modeling tools, given existing building load profiles. These measures do not drive design and if used to size thermal resource requirements, such as borehole fields, will result in an overdesigned system with unnecessary cost. This first set includes the *buildings peak load* and the *buildings annual load*.

3.1.1 Buildings Peak Load$_{(i)}$ (BPL)

This is the sum of all the individual building peak hourly loads met over a given year (BTU/h, tons or kW_{th}), before connected to a network *i*. The peaks are non-coincident, and are reported for heating *H* and for cooling *C*. For a network *1*, the sum of BPL_{H1} and BPL_{C1} results in BPL_1.

3.1.2 Buildings Annual Load$_{(i)}$ (BAL)

This is the sum of the absolute value of individual building hourly loads for heating and for cooling over a given year (BTU, ton-h, or $kW_{th}h$) before connected to a network *i*. For network *1*, the sum of $|BAL_{H1}|$ and $|BAL_{C1}|$ results in $BAL_{1.}$

The second set of measures, the *network loads*, are pertinent to the actual design of a single-pipe ambient loop, and these measures require transient or semi-transient modeling tools. The factors influencing the network loads are: (1) coincident building load peaks, (2) heat pump thermal energy flow, (3) horizontal network pipe thermal exchange, (3) pump thermal waste, and (4) the load flattening effects of the dynamic thermal inertia of the water in the distribution system loop, referred to as the 'thermal flywheel' and (5) the selected design temperature window. Each of these steps could be considered an interim load calculation and further exploration of the impacts of each element is an area of further inquiry. Nevertheless, taken together they result in a different load profile, representative of the actual load that needs to be met by the thermal resources, such as borefields. This second set of measures includes the *network peak load* and the *network annual load*.

3.1.3 Network Peak Load$_{(i)}$ (NPL)

This is the peak hourly load of the network 'loop' *i* that connected thermal resources must meet for both heating and cooling over a given year (BTU/hr, tons or kW_{th}), with all buildings connected. For network *1*, this measure is reported for heating *H* as NPL_{H1} and for cooling *C* as NPL_{C1}. The sum of NPL_{H1} and NPL_{C1} results in NPL_1.

3.1.4 Network Annual Load$_{(i)}$ (NAL)

This is the sum of the absolute values of coincident hourly loads of the network 'loop' *i* that connected thermal resources must meet for heating and for cooling over a given year (BTU, ton-h, or $kW_{th}h$) with all buildings connected. For network *1* this measure is reported for heating *H* and for cooling *C* as $|NAL_{H1}|$ and $|NAL_{C1}|$ respectively. The sum of $|NAL_{H1}|$ and $|NAL_{C1}|$ results in NAL_1.

The proposed definitions will not only allow for more accurate comparisons of capacity between different systems but also more accurate comparisons between costs, savings, scaling benefits, and minimum viable scale for investment. Some such implications for the TENs ecosystem were described by HEET (2026) as follows,

- The BPL should be used for comparison to alternate energy system(s). Furthermore, when doing comparisons, these alternate energy systems (such as air-source heat pumps) should also consider reporting the BPL for both heating and cooling.
- Comparisons (and life cycle assessment) should include both heating and cooling.
- The NPL is related to system deliverability and the NAL is related to system capacity, together they are central to cost effective design and infrastructure investment.
- The difference between building and network loads quantifies a new form of network energy efficiency or evaluation of performance.
- Reducing the difference between modeled and actual network loads can lead to lower costs.
- All TEN systems should report each load with a consistent nomenclature.

3.2 Reporting System Size of the Framingham GEN

Eversource has been an industry leader on utility deployments of geothermal networks since 2019. As the Framingham Phase 1 and Phase 2 have progressed and the understanding of system modeling, performance, and loads have advanced, the reporting measures have also subsequently adjusted. This makes the Framingham GEN an excellent learning opportunity and a leading example to illustrate the need for an industry standard on reporting load measures.

In sizing the borefield for the planned Flagg loop, the potential heating and cooling load or NPL load was calculated using the TRNSYS (Klein et al., 2018) model of the loop. The building loads that were input into the model were based on the square footage of all potential participating buildings in the Flagg loop and the scaled load profiles from the adjacent operational Concord loop. While there is still uncertainty if all potential building owners along the Flagg loop will choose to participate in the geothermal network, the project utility infrastructure is designed to facilitate future scaling and growth of the system.

Table 4: System size for the Concord loop (Phase 1) and planned Flagg loop (Phase 2). Building peak load (BPL) refers to the sum of all individual building peak hourly loads met over a given year, and network peak load (NPL) to the peak hourly load of the GEN loop itself, which accounts for transient modeling of energy sharing between buildings, and thermal storage in the borefield and main loop among other factors.

Reporting Measure	Load Type	Units	Phase 1	Phase 2	Phase 1+ Phase 2
NAL_C	Annual Cooling	**tons**	**209,098**	**227,264**	**436,362**
		$kW_{th}h$	735,398	799,286	1,534,684
NAL_H	Annual Heating	**tons**	**399,765**	**450,581**	**850,345**
		$kW_{th}h$	1,405,972	1,584,692	2,990,664
BPL_C	Peak Cooling	**tons**	**222**	**303**	**525**
		kW_{th}	781	1065	1846
BPL_H	Peak Heating	**tons**	**257**	**350**	**607**
		kW_{th}	904	1231	2135
NPL_C	Peak Cooling	**tons**	**138**	**322**	**460**
		kW_{th}	486	1132	1618
NPL_H	Peak Heating	**tons**	**105**	**193**	**297**
		kW_{th}	369	677	1046

As proposed in section 3.1, Table 4 demonstrates two ways to present the borefield and loop capacity for the Framingham GEN system. The network peak load (NPL) values in Table 4 are the modeled loads that the network system is expected to experience. They take into account diverse load cancellation, time of day load factors, and other efficiencies observed on networks. The buildings peak load (BPL) is an alternative presentation of system capacity that shows the aggregate load served or building load connected to the network. In the case of the Concord Loop, this was generally reported as approximately 375 tons for peak heating, or BPL_H, and was based on the summation of each of the peak building loads. More recent modeling performed during this study, that includes more building performance data and equipment observations and adjustments, estimates this measure at 257 tons (Table 4). The BPL_H for the Flagg loop has been reported previously as ~421 tons (DPU 21-53), with this study adjusting that measure to ~350 tons (Table 4). The BPL capacity number can be used to determine how much alternative fuel or energy source heating and cooling is being replaced by the new geothermal network. The difference between the BPL and NPL is a representation of the efficiency of the network. It shows a reduction in thermal resources needed to meet the thermal needs of buildings when they are connected to a network. The combined BPL measure of Phase 1 + Phase 2 networks, or BPL_{1+2} is 1132 tons, and the combined NPL_{1+2} is 758 tons, which indicates an estimated thermal peak load reduction of 374 tons, or 33% less thermal resources needed by the GEN, as a result of networking the buildings together.

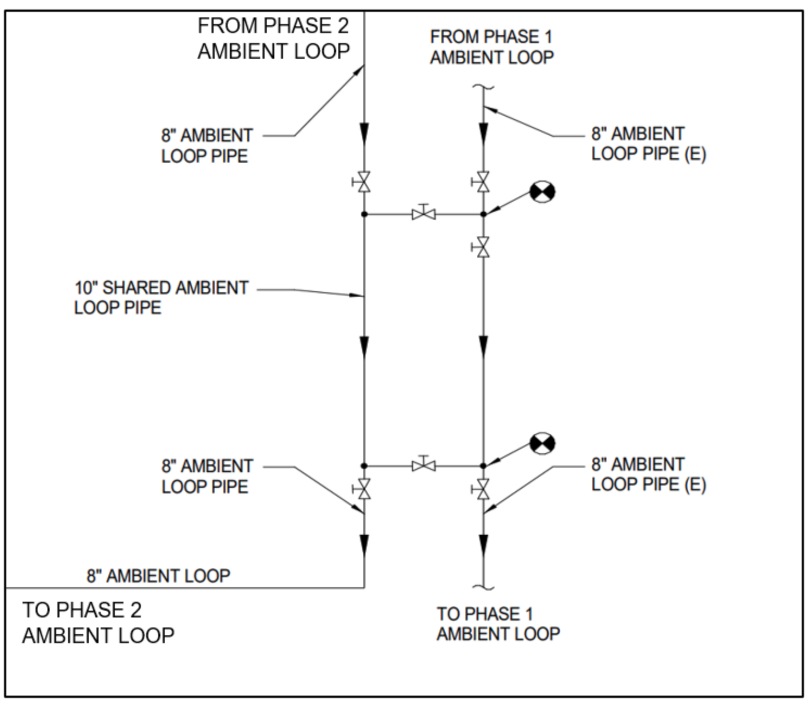
4. GEN Loop Interconnection

One aspect that makes this Framingham project unique is the study of how to optimally expand GENs by interconnecting GEN loops. This section explores several different potential interconnection approaches between two loops.

Since Phase 1 was a first-in-the-nation pilot, the main mechanism implemented to support future expansion was the selection of a single pipe loop set-up, as it is more conducive and cost effective to expandability compared, for example, to a 2-pipe system. Considering this is the first expansion to an existing geothermal network, as the expansion design progressed, the design team focused on finding the mechanical connection for optimal performance of both loops and, finding the interconnection design that would result in minimal disruption to the already operational loop.

4.1 The Butterfly Piping Interconnection

The butterfly[1] connection was selected for Framingham as it was found to be the most efficient method to interconnect the two loops. The Flagg loop was designed to connect to the Concord loop through two 20 ft sections of 10 inch diameter pipe at the north end of Rose Kennedy Lane and the south end of Berkshire Road as shown in Figure 1. The Phase 2 loop will connect to the existing Phase 1 loop with a series of valves that could isolate the loops from one another if needed. This design, referred to as the Butterfly Piping Design is shown in Figure 6. The 20 feet of shared ambient loop pipe serve as two balancing thermal resources on either loop. Between these two mixing pipes will run two parallel 8 inch pipes serving the Flagg loop and the Concord loop. The butterfly connection provides an efficient way to connect the two loops while minimizing the disruption of the operational loop.



[1] This connection stabilizes a dynamic system.

Figure 6: A mechanical drawing of the proposed mixing area of the Concord and Flagg loops. The shared ambient pipe would be roughly 20 ft long

4.2 Alternative Interconnection Designs

An upsized single pipe could serve as a loop interconnector but the pros and cons need to be considered. An alternative interconnection design could be the two loops sharing a longer section of pipe with a larger diameter through Rose Kennedy Lane and Berkshire Road. This Shared Pipe Design may increase pumping power requirements on an individual loop that would otherwise utilize a smaller diameter pipe, but will decrease pumping power requirements as compared to the Butterfly Piping Design where two 8 inch pipes are located parallel to each other. However, this design makes it more difficult to isolate one loop in the case that the other is experiencing issues. It also requires scalability and expansion planning to be carefully considered as part of the project.

Sharing fluid between loops requires maintenance and monitoring of the working fluid. Both of these interconnection designs, the butterfly and single upsized pipe, allow for exchange of ambient loop liquid between the two systems. Because of this, the Flagg loop was designed to operate with the same percentage of glycol in water as the Concord loop. Sharing the working fluid between loops increases the importance of regular system maintenance and fluid quality monitoring. If there is air, or debris is introduced into one loop, it will be circulated through all interconnected loops. Air bubbles and debris can cause significant issues in the commissioning of a GEN. Incorporation of sufficient air traps and filters can mitigate these risks.

An alternative mode of interconnection is by transferring thermal energy between the loops through a heat exchanger. Thus, this method does not require the mixing of the working fluids. However, compared to the methods where the working fluid itself is shared between the loops, this heat exchanger method has a lower efficiency on the thermal transfer. This study determined not to explore the heat exchanger interconnecting design approach or cost in detail.

One recommendation from this study for the design of GENs is to leave in place options (stub-outs, upsized pipe, or heat exchangers) for potential future expansions to minimize the disruption of the existing infrastructure and services, even if the future distribution loops are in the pre-feasibility stage.

5. Modeling Results of Thermal Load Balancing Between Loops

In designing the Flagg loop, heating and cooling loads were estimated for all loop-adjacent buildings. A detailed energy model of the loops was developed in TRNSYS (Transient System Simulation tool) which simulates the entire system over time, allowing for analysis of interdependent thermal interactions between the borefields, buildings, and the hydronic piping network. The model includes the buildings' heat pumps, fluid pumps, and heat exchangers, the borefields, buried ambient loop pipes, the ambient and geothermal pumps, and complex controls for the system. The model was simulated over three years. Two different Flagg loop designs were compared: one with an additional 20-bore borefield, and one with a 175 kW electric boiler instead to help meet peak demand. In addition, the Flagg loop and Concord loop temperatures were modeled alongside each other both with and without loop mixing. In all cases, when the two loops were mixed the operating temperature remained within a narrower range than if the loops were operating independently, signaling an increase in system efficiency when interconnected.

5.1 Model of Flagg loop with Additional 20 bores

The modeling of Phase 1 and Phase 2 was performed using a transient system simulation program (TRNSYS) (Klein et al., 2018). Figure 8a shows the Phase 1 and 2 ambient loop temperatures at each point on the loop at the coldest hour of the model built in TRNSYS. Each label 1 through 7 represents the corresponding location on the site map shown in Figure 7. The Phase 1 and Phase 2 lines begin and end at the butterfly piping connection between each ambient loop near the intersection of Prindiville Avenue and Berkshire Road as labeled in Figure 7. Because both loops share the same pipe at this point, they also share the same temperature. From there, the Phase 2 loop line proceeds west along Prindiville Avenue and up Warren Road to Flagg Drive where the additional GHX is located. During the winter, the ambient loop temperature increases at the additional GHX located at points 2 and 3 as graphed in Figure 8a. From there, this added heat is shared with the Phase 1 at the butterfly piping connection on Normandy Road. Then heat is extracted by each building until the loop reaches point 1 again.

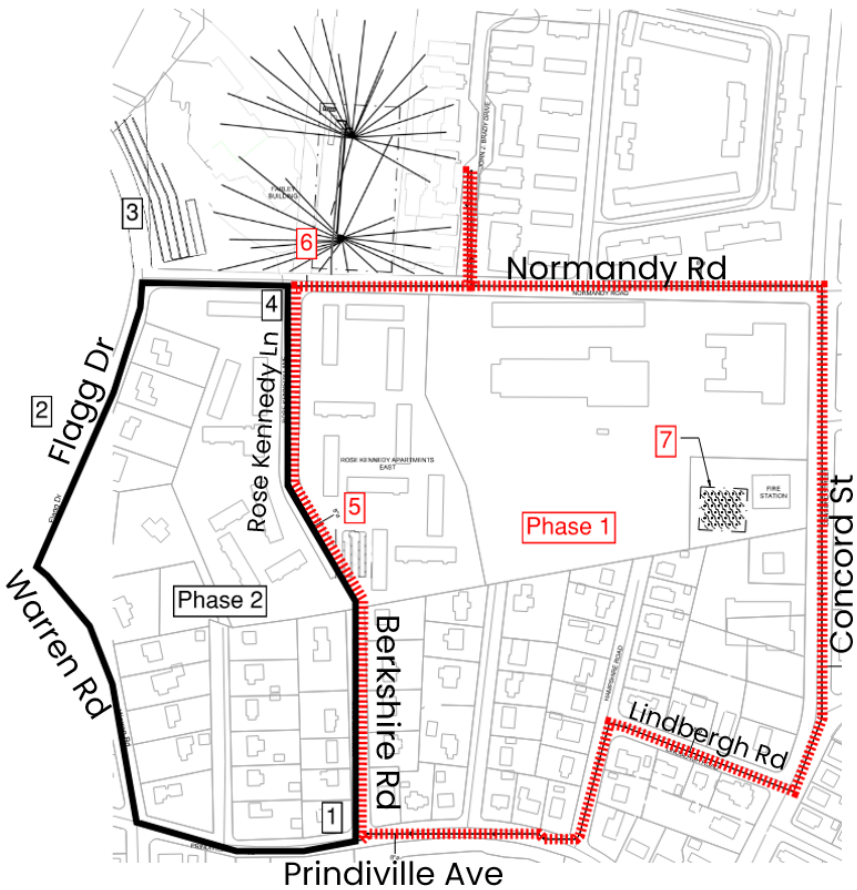


Figure 7: shows the Phase 1 and Phase 2 ambient loop layouts as they have been modeled in TRNSYS, along with some important points in each loop. Points 1 and 4 are the two spots in the system where both ambient loops converge into one pipe, mixing fluid from each loop together and allowing for heat sharing between loops. The Phase 2 borefield is located at point 3, while the three Phase 1 borefields are located at points 5, 6, and 7. Point 2 represents the modeled location of a potential new borefield with 20 bores.

The Phase 1 loop in Figure 8a also starts at point 1 and proceeds east on Prindiville, picking up heat at the GHX at point 7. Then it goes through the housing authority buildings before picking up heat again at the GHX at point 6. Then at point 4 the loops converge on Normandy Road and share heat. Overall, because both the Phase 1 and Phase 2 temperatures remain at or above 37°F in Figure 8a, these results meet the ambient loop design requirements.

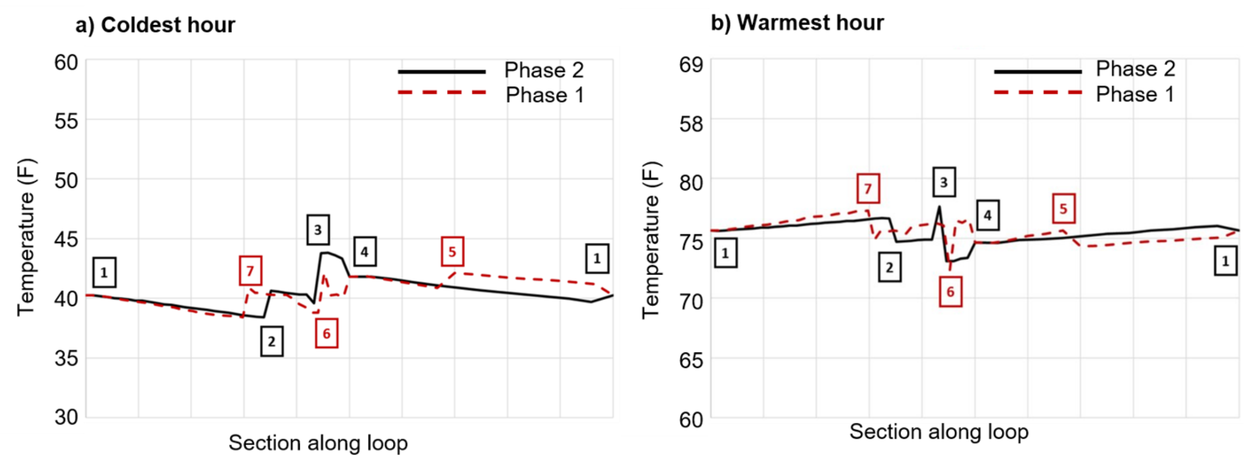


Figure 8: Temperatures throughout the Concord (Phase 1) and Flagg (Phase 2) loops modeled in TRNSYS for the coldest and warmest hours of the year with an additional 20 bores at Point 2.

Similarly to the coldest hour of the year shown in Figure 8a, Figure 8b shows the modeled temperature along both loops for the warmest hour of the year.

Figure 9 shows the average temperature modeled across the ambient loop at each hour for three years. Note that these are different from Figure 8, which shows the temperature across the ambient loop at one given hour. The temperatures in Figure 9 are within the designed ambient loop temperature range, fluctuating between 40 °F and 76 °F over the course of three years and enabling efficient heat pump operation. Additionally, Figure 9 shows that the average annual temperatures are not expected to fluctuate from year to year. This is due to proper GHX sizing, balanced annual heating and cooling loads, and heat sharing between the ambient loops. Consistent ambient loop temperatures year over year are a strong indicator that this system is properly sized and designed to last for years to come.

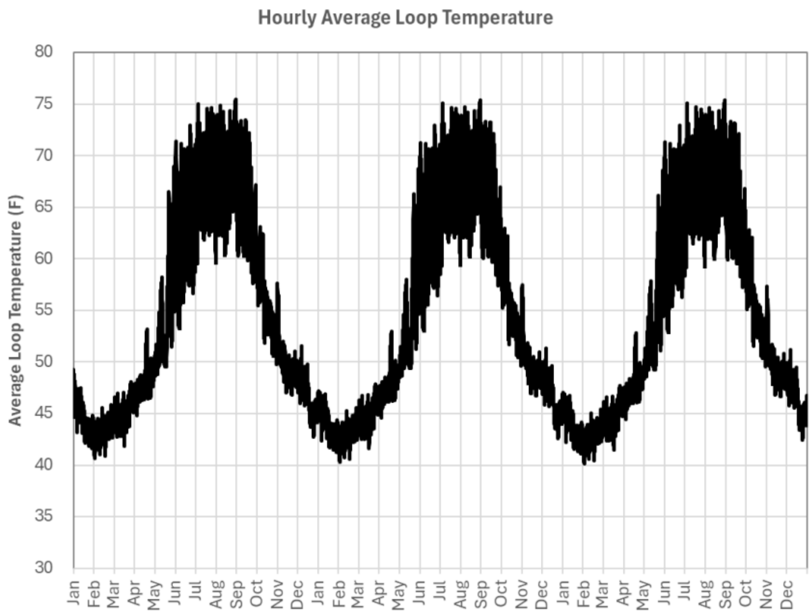


Figure 9: Hourly annual Phase 2 loop Temperature modeled in TRNSYS with an additional 20 bores incorporated. The model shown spans 3 years.

5.2 Model of Flagg loop with Additional Electric Boiler

For the Flagg loop, an alternative model was developed in TRNSYS where an electric boiler was incorporated instead of the additional borefield with 20 bores. Figure 10 shows the temperature along the main loop for the coldest and warmest hours of the year with the electric boiler. Additionally, Figure 11 shows the hourly annual temperatures for the Flagg loop spanning 3 years.

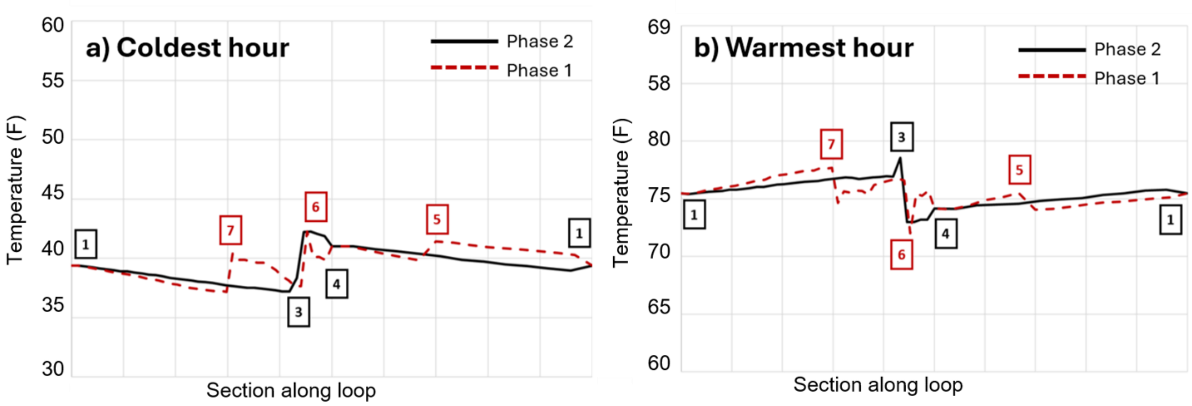


Figure 10: Temperatures throughout the Concord (Phase 1) and Flagg (Phase 2) loops modeled in TRNSYS for the coldest and warmest hours of the year with an additional electric boiler at Point 3.

In both the model with the additional borefield and with the electric boiler, the ambient loop temperature remained within the design range of 37°F and 90°F. Because the Flagg loop has thermal resources concentrated at the school (next to point 6 in Figure 7), incorporating two mixing locations with the Concord loop essentially provides two additional thermal resources to help normalize temperatures throughout the loop. Utilizing the electric boiler, temperatures fluctuated between 38°F and 76°F over 3 years, as shown in Figure 11. This indicates that an electric boiler could effectively replace an equivalent of 20 bores on the Phase 2 ambient loop if desired, allowing for a reduction in the total number of bores. For the Concord loop, bores were a significant part of the capital cost of construction.

The Framingham GEN already has a backup electric boiler. The Concord loop has an electric boiler that was installed for the event that the three different borefields that service the loop would not be able to maintain the optimal operating temperatures during extreme cold weather. However, in the two years since the Concord loop has been operational, the electric boiler has not been used at all, as the borefields have been able to maintain the temperature in the main loop within the desired range. On January 24, 2026 the Concord loop system experienced the coldest hour of the year, with an outdoor temperature of 8.9 °F, and yet the temperature in the main loop remained at 41.78 °F without the use of the electric boiler.

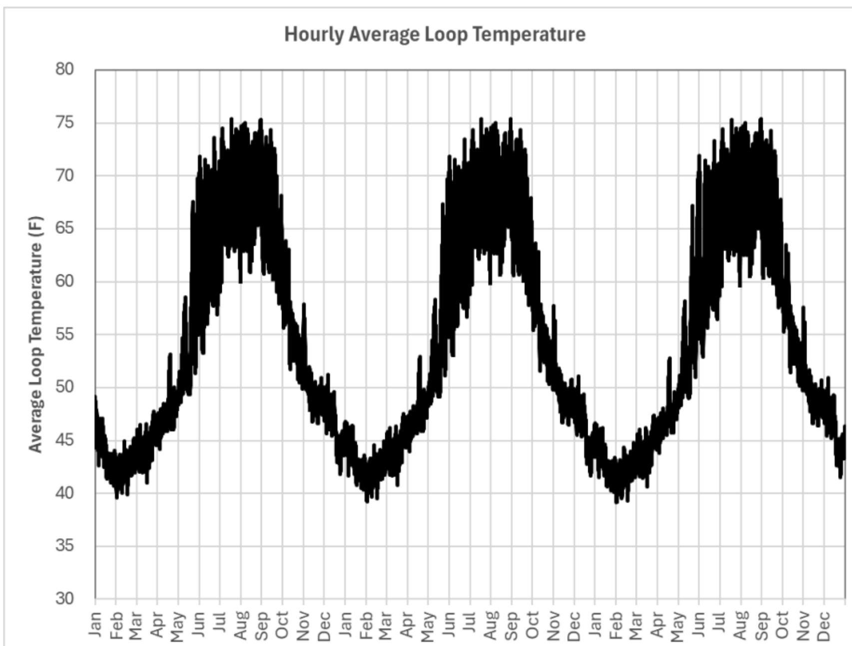


Figure 11: Hourly annual Phase 2 loop Temperature modeled in TRNSYS with an Electric Boiler incorporated at Point 3. The model shown spans 3-years.

6. Network Growth (Beyond Phase 2) Implications for Design

The Framingham GEN is utilizing a Butterfly Piping Design for thermal exchange between Phase 1 and Phase 2 in order to minimize disruption to service on the operational Phase 1. However, as there is pre-emptive planning for potential future expansion (Phase 3+) of the project by the interconnection of additional adjacent loops, a shared upsized pipe is being considered on the Flagg loop project along Warren Road (Figure 7) to allow for easier expansion of future Framingham GENs.

6.1 Pipe Stub-outs for Adjacent Buildings

The borefield for Flagg loop was designed assuming the load of the network would include all potential buildings adjacent to the ambient loop route. With funding limitations and the assumption of less than 100% adoption by all residents on the loop, the project is planning for the event that in the first years after commissioning, the GEN could be serving a smaller subset of buildings. In order to allow for a seamless eventual future inclusion of additional buildings, the Flagg loop will include ambient loop stub-outs for potential future service lines. Including these pipe stub-outs adds minimal construction cost to the project and offers the opportunity for future connection with no significant disruption to the operational loop.

6.2 Interconnection Options for Dead End Streets

As initially planned, the Flagg loop project does not include geothermal service to abutting dead end streets. Although there are multiple reasons favoring the inclusion of dead-end streets into the project, the additional costs cannot be currently accommodated within Phase 2. Nevertheless, the Phase 2 design is planning for the potential future inclusion of the dead-end streets by leaving pipe stub-outs which will facilitate a streamlined and minimally disruptive inclusion in the future if needed (Phase 3+).

There are multiple ways in which dead-end streets could be connected to a GEN loop if desired. The design team considered strategies for connecting service to dead-end streets that abut the main ambient loop. For smaller dead-end street segments that serve on the order of 4 residences, the team considered the possibility of laying supply and return lines in the street to serve these buildings. This system would essentially function as a small 2-pipe system on the dead-end street that ties to the single pipe main loop. For dead-ends serving more buildings and larger thermal load, the main ambient loop would have to be expanded down the street to avoid the potential for operating temperatures in the main distribution loop to drop outside of the desirable range.

6.3 Isolating Critical Facilities

GENs provide additional resiliency benefits and “islanding” or isolation options for network facilities that host critical infrastructure. For example, as part of the Flagg loop growth, the design team is facilitating the connection of nearby buildings from the National Guard into the GEN system. As part of this effort, the engineering team completed 30% and 60% engineering designs for the National Guard to host a borefield and connect to the Phase 1 loop. As critical infrastructure, the National Guard base was designed to be able to operate either in connection with the larger loop or isolated from it. A borefield with 30 bores was designed for the National Guard base that could serve the two conditioned buildings. When possible, the borefield at the base could remain connected to the larger loop to aid in load balancing the main loop, as the base buildings have different heating and cooling demands from the other connected buildings. If desired, the base could be disconnected from the main system via manual valves to operate independently. This option to “island” itself not only offers additional risk mitigation for the base, but also allows for more future flexibility in the overall operations of the main GEN system.

7. Ownership Demarcation Implications for Design

As the utility adoption of GEN systems expands, defining the line of ownership demarcation between the utility and the customer becomes necessary. During the demonstration phase of GEN systems these ownership models may present more variability, as is the case even between the

Concord and Flagg loops. Within the Concord loop in Framingham, all infrastructure and equipment belong to and are the responsibility of Eversource for the duration of the pilot period. During that timeframe, the ownership and operations and maintenance responsibilities are clearly with the utility. In the Flagg loop, the ownership of the equipment inside the buildings will remain with HEET for a limited duration after which it will be transferred to the participants in the loop, necessitating the definition of a line of demarcation between utility ownership and private ownership.

7.1 Commercial buildings

In commercial buildings served by the Framingham GEN, the ambient loop is connected to the building side loop through a heat exchanger. In the proposed ownership model for these buildings in the Flagg loop, the utility owns all infrastructure up to and including the heat exchanger. The building side loop beyond the heat exchanger will be owned by the building owner, as well as any piping, circulation pumps, heat pumps, etc.

7.2 Residential Buildings

Three potential models for the line of ownership demarcation between the residential building participants and utility were evaluated:

a) Demarcation behind heat exchanger - Outside the home: This scenario involves installing a heat exchanger at the service line outside each home as depicted in Figure 12a. This would require digging a vault for the heat exchanger, incurring additional installation and maintenance costs. In this scenario, the utility would not own or service any equipment inside a private residence.

b) Demarcation behind heat exchanger - Inside the home: This scenario would require installing a heat exchanger inside the homes as illustrated in Figure 12b. This would result in increased installation and maintenance costs while also requiring utility access to the homes. Notably, this scenario does not completely eliminate the risk of pipes leaking inside the home, but greatly reduces the amount of exposed pipe that is directly connected to the loop.

c) Demarcation behind-the-valve (BTV) - Inside the home: This scenario does not include an additional heat exchanger and also does not require utility access to the homes after installation as illustrated in Figure 12c.

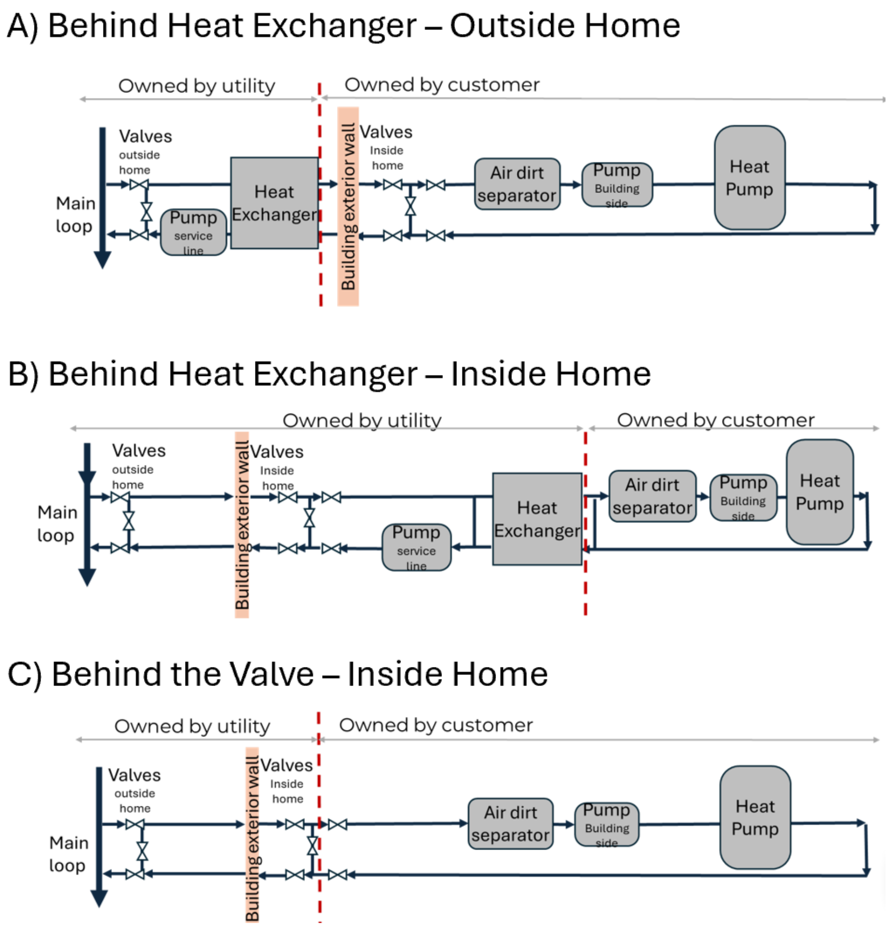


Figure 12: Diagrammatic sketch showing the line of demarcation scenarios described in Table 3. Ownership line of demarcation shown in red dashed line for all scenarios.

A summary comparison of each of these scenarios is represented by color in Table 5, with benefits and drawbacks represented by green and red respectively, and yellow denoting neutrality. The analysis shows that scenario c) demarcation behind the valve - inside the home, presents most benefits, and scenario a) demarcation behind the heat exchanger - outside the home, presents most drawbacks.

For GENs, behind-the-valve (BTV) replaces the behind-the-meter (BTM) terminology often used by utilities in reference to the customer ownership of equipment in their homes connected to the gas or electric system. For residential single family buildings, the proposed ownership model is for the utility to own the service lines and the connection up to the valve immediately after the service line enters the building as depicted in Figure 12c. All piping and equipment (circulation pumps, heat pumps, etc.) behind-the-valve would be owned by the building owner. This would include the service pump to the building and the electricity costs to operate it.

Note that in residential buildings along the Flagg loop, it was determined not to incorporate a heat exchanger for building service as discussed in the next section.

Table 5: Comparison for different line of demarcation scenarios for the residential buildings. a) Demarcation behind the heat exchanger outside the home, b) demarcation behind the heat exchanger inside the home and c) demarcation behind the valve inside the home. Colors denote benefits (green); drawbacks (red); or neutrality (yellow).

Parameter	A) Demarcation Behind HX Outside Home	B) Demarcation Behind HX Inside Home	C) Demarcation Behind the Valve
Installation cost	$$$$	$$$	$
Maintenance cost	$$$$$	$$	$
Extra service line pump	Required	Required	NA
Extra heat exchanger	Required	Required	NA
System Efficiency Loss	-2%	-2%	NA
Reduces risk of malfunction in home equipment affecting loop	Yes	No	No
Utility requires regular access to homes for maintenance	No	Yes	No
Requires extra space in home basement	No	Yes	No

7.3 Should Heat Exchangers be Installed at Each Service Line?

Upon an initial analysis, considering the installation of heat exchangers at each service line seems beneficial. Installing a heat exchanger close to the stub-out from each service line ensures that the fluid circulating in the main loop does not go into each building and vice-versa. The main benefit from this is that if there ever is an issue in the piping inside a building the performance or operations of the main loop would not be affected. In other words, the risk of leaks in a building affecting the main loop would be avoided. However, the incorporation of heat exchangers at each building presents several difficulties.

The first difficulty is in locating the equipment. If a heat exchanger needs to be located within a residence, common space constraints in homes can result in challenges in finding an appropriate location for placement. Second, the utility would require periodical access to the heat exchanger for maintenance, which presents a logistical scheduling challenge between the utility and the customer. Third, locating the heat exchanger inside the home still results in ambient loop fluid entering the building, so the risk of potential problems inside the building affecting the main loop is not completely eliminated. Fourth, heat exchangers themselves would add to the overall price tag of the project if incorporated at every building, and they also have a negative impact on loop and building level efficiencies. Alternatively, a heat exchanger may be located in a vault outside of the building; however this presents a significant cost increase related to construction and maintenance of the vault.

In the Flagg loop, the decision was made to incorporate heat exchangers only in the commercial buildings (a school building and a housing authority apartment building) and to serve residential buildings without a heat exchanger. In order to mitigate risk of leaks in the residential homes that will not have a heat exchanger, flow limiters and sensors are considered at building entrances to indicate if a leak has occurred. While pressure sensors in the loop will report a drop in pressure if the system starts leaking, they will not indicate the location of the leak. To mitigate any potential issues, valves will be incorporated immediately at the entrance into the residential homes, and heat pump equipment will be located close to the valves to minimize pipe stretches carrying ambient loop fluid within the building.

8. Vault Design

For the Flagg loop, an underground vault was initially designed for housing of loop infrastructure such as the pumps, valves, and ambient temperature water piping. While an above-ground structure was used in the Concord loop, an underground vault could offer construction cost savings and be less visible from a community stakeholder perspective. Additionally, because of potential siting challenges in some locations for an above-ground structure, a below-ground option potentially facilitates scalability for geothermal networks. For this project, however, this design decision was largely influenced by the utility partner, who recently adopted a policy to avoid building permit-required confined space, including below ground vaults, as part of their utility infrastructure.

A below ground vault space would be classified as *confined* by the following federal regulations (Confined Space, 2026):

1. The space must be large enough and so configured that an employee can bodily enter and perform assigned work, and;
2. The space must have limited or restricted means for entry or exit, and;
3. The space must not be designed for continuous employee occupancy.

While the project team was comfortable designing confined space into the system for this project, the team attempted to avoid designing a permit-required confined space. The utility provider that would be servicing and maintaining the vault strives to minimize permit-required spaces as they have the potential to be more dangerous and require specialized training for employees to enter. This training adds cost and complexity to the maintenance of the system. *Permit-required confined space* is a confined space that meets at least one of the following criteria (Permit required confined space, 2026):

1. The space contains or has a potential to contain a hazardous atmosphere, or;
2. The space contains a material that has the potential for engulfing an entrant, or;
3. The space has the internal configuration such that an entrant could be trapped or asphyxiated by inwardly converging walls or by a floor which slopes downward and tapers to a smaller cross-section, or;
4. The space contains any other recognized serious safety or health hazard.

In order to minimize risk, the underground vault was designed as a single large space to house both borefield and ambient loop service equipment. The geothermal manifold that was previously designed to be contained in a second vault was redesigned to be accessed via direct buried valves. The vault design was roughly 17’x19’ with 9’ vertical space. The floors would be minutely graded to drain any liquid into a sump pit with a sump pump. The space would have three access points: two staircases covered by hatch doors and an additional ladder with a hydraulic panic bar hatch. The doors would be connected by a continuous open pathway from east to west. The pipes in the vault would contain water and 25% glycol at ~45°F and 30 PSI. In the event of a pressure drop, the pumps would automatically disable. All piping would have manual shut off valves within the vault at each pipe/wall penetration.

The engineering team determined that a catastrophic leak producing peak possible flow from the full system through one of the 8 inch pipes would produce approximately 500 gpm of fluid. Based on the underground vault design, the space would fill at a rate of roughly 2.5 inches per minute in the catastrophic leak scenario. A more realistic leak from a worn seal or valve flange issue would produce a much smaller leak that could be managed by the sump pump.

Consideration of risks related to vaults and pump houses for water pumping equipment is uncommon for gas utility safety teams. The utility safety team determined that water passing through pipes in an underground vault had, in the case of a leak, the potential to pose an engulfment risk, which would classify the space as permit-required. Uncertainty around standards and best practices for such infrastructure, together with tight project timelines and reasonable local feasibility for an above ground structure resulted in selection of this more conservative design choice. The selection of the above-ground pumphouse design avoided the potential for the vault space to be classified as a permit-required confined space, thereby reducing risk, and cost-effectively placed the structure at the borefield location next to the school building. While this was the design selection for the Flagg loop project, with expert consultation and safety mitigating design details, an underground vault design remains a feasible option for future projects.

9. Conclusions

This study presents multiple learnings related to the design process for the Flagg loop, the first utility-led GEN system to connect to an already operational GEN loop. The intention of sharing this work is to contribute to the body of work related to design best practices for growing GEN systems.

One of the main conclusions of this work is that connecting adjacent loops increases the efficiency of the overall system, driving scalability. Separate ambient loops were considered early in the design, but heat sharing between loops via a 'butterfly' connection resulted in optimal ambient loop temperatures requiring the fewest number of bores. An additional learning is that proactively planning for interconnections (e.g., piping stub-outs, outsize pipe sections, and/or heat exchangers) to any potential future loops (even if they are in the prefeasibility stages) minimizes future disruptions when the system expands into adjacent loops and saves both cost and time.

Other findings come from the systematic exploration and comparison of various borefield design configurations. Multiple variables were considered in these borefield scenarios, including bore layout (grid, line, clusters), surface spacing, trajectory (vertical, inclined), style of heat exchanger (single U-tube, double U-tube, concentric), depth, and modeling technology. Each variable may be altered to meet specific project needs or constraints, such as available surface area for drilling, workforce, procurement, cost, or peak loads. In the modeling performed, inclined bores presented a similar performance to vertical bores. By modeling borefield leaving water temperatures for the different borefield configurations, a borefield with either vertical or inclined bores was selected for the Flagg loop pending further definition of project constraints.

This study proposes the use of standardized measures in the reporting of the size of GEN systems as a systematic approach to compare costs and efficiencies not only between different GEN systems but also between different heating and cooling technologies. We introduce the *building* and *network loads* measures for both heating and cooling. While the sum of all individual building peak hourly loads of each building on a loop represents one measurement of load (referred to as *buildings peak load*, BPL), thermal balancing and load cancellation allows for a GEN of a smaller measured capacity (*network peak load*, NPL) to meet the needs of all buildings. This smaller network load NPL represents a different measurement of GEN load. The difference between BPL and NPL is then a representation of the efficiency of a geothermal network. Using these proposed measures for the Flagg loop results in an estimation of a 33% thermal peak load reduction due to networking. Thus, this highlights how the method for describing the size of a GEN is critical to understanding outcomes, costs and optimization.

This study also proposes a line of ownership demarcation between utilities or developers and GEN participants that could be applicable to other GEN systems. Defining a common ownership line of demarcation is essential for the scaling of GEN systems with some uniformity. For residential buildings this study proposes avoiding the installation of an additional heat exchanger and defining a line of ownership demarcation at a valve immediately inside the building. Thus, behind-the-valve (BTV) would replace the equivalent behind-the-meter (BTM) for gas and electric services, where the customer owns and maintains all equipment. For commercial buildings this study proposes the use of a heat exchanger as the line of demarcation, where the utility owns the service line up to and including the heat exchanger.

Additionally, this study explores other GEN design features such as the use of a backup electric boiler to reduce the number of bores needed and thus reducing capital costs. This project also considered the possibility of islanding a set of critical infrastructure buildings from the loop if needed to increase their resiliency. Lastly, key decision parameters for the selection of above ground or below ground pumping structures were analyzed.

The Flagg loop in Framingham is a first-of-its-kind project in its design of a utility-operated geothermal network expansion connected to an already operational system. As such, the design considerations of the system have few direct reference cases. Learnings from the Framingham GEN system will continue to be captured as the project moves to the construction and commissioning stages in 2027. While each GEN will present its own intricacies and challenges, elements of learning from the Flagg loop design work presented in this study can be used to inform design thinking of future utility-scale projects.

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Authorship

Rose Sears - Energy Engineer at Salas O'Brien. Rose completed geothermal modeling in TRNSYS and GLD, modeled the Framingham ambient loop in TRNSYS and wrote sections related to borefield modeling, GEN sizing and GEN design. Brian Urlaub - Director of Geothermal Operations and Senior Vice President at Salas O'Brien provided executive and technical supervision of the project. Jeff Thornton - TRNSYS Modeling Expert and Senior Vice President at Salas O'Brien provided TRNSYS modeling oversight. Marisa Dunning - Energy Engineer at Salas O'Brien completed thermal profile modeling and wrote sections related to TRNSYS modeling. Daniel Deacon - Geothermal engineer at Salas O'Brien completed the COMSOL modeling. Isabel Varela - Science Director at HEET is the Principal Investigator for the DOE award and led the overall paper conceptualization, writing and editing. Additionally, she led the line of demarcation work and provided project technical oversight and management. Kari Bender - Research Project Manager at HEET, led the vault discussion, project management, paper writing and editing. Grace Watters - Clean Technologies Program Manager at Eversource edited the paper and managed Eversource's contribution to the project. Leen Hayek - Supervisor, Clean Technologies, edited the paper and supervised Eversource's contribution to the project. June Wooding - Manager Clean Technologies, edited the paper and provided project oversight. Eric Bosworth, Principal at Thermal Energy Insights, contributed to the borefield sizing measures section. Zeyneb Magavi - Executive Director at HEET, provided project conceptualization and oversight, led the GEN sizing measures definition, and edited the paper.

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