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SuperCOPs: Hybrid Geothermal Heat Pump Systems for Exceptional Economics, Environmental Performance, and Operational Control

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ABSTRACT

The use of heat pumps with exceptional Coefficients of Performance (COP), "SuperCOP", systems can enhance geothermal operations. This paper describes design concepts that optimize SuperCOP effectiveness and examines a working system in the Dogger Basin.

Systems that extract heat from the ground are typically categorized into two types. The first type uses heat pumps (or heat recovery chillers) connected to piping systems that extract (or exchange) heat from relatively shallow ground loops or wells. The second type uses deeper and hotter geothermal fluids directly without heat pumps. This paper reviews a third type of geothermal system with distinctly different design parameters and benefits compared to either of these primary types. This "hybrid" system relies on circulation of geothermally heated fluids as a primary energy source but also incorporates custom heat pump(s) deployed centrally or in various localized configurations, selected for high COP performance.

Overall, a well-designed SuperCOP system can enrich system economics, enhance operational control, extend system life, and improve environmental performance compared to either of the typical primary systems. These advantages significantly reduce the financial risk posed by developing low temperature (below ~90ºC) geothermal resources.

Both modeling results and actual operating data demonstrate these advantages. Modeling results from a Cornell University study, funded by the U.S. Department of Energy, demonstrate potential benefits and quantify the energy implications of various system arrangements. Operating data using a recently commissioned system operating in the Dogger basin just outside Paris, France demonstrate one practical application where geothermal production is more than doubled through integration of heat pumps. Methods for further optimizing the performance of geothermal systems is discussed in the context of on-going and proposed research involving SuperCOP technology, expanding the range of economically feasible applications for heating using lower temperature geothermal resources.

1. INTRODUCTION AND OUTLINE

In northern climates globally, heat for buildings and for industrial and agricultural processes is a substantial and often underestimated source of greenhouse gas emissions (GHGs). Many northern areas use fossil fuels (coal, oil, gas) for heating. Heating with woody biomass is also common, but the quantity of biomass needed for heating in northern climates, and the particulate emissions typically associated with biomass combustion, limit the extent to which biomass can be used as a primary source of heat.

Two common types of systems that extract heat from the ground for heating facilities or processes are typically used. The first type use heat pumps (or heat recovery chillers) connected to piping systems that extract heat with the earth via relatively shallow ground loops or wells; these are called "ground source heat pump" (GSHP) or "geothermal heat pump" systems. These systems utilize the relatively steady temperature of the earth to improve seasonal heat pump performance compared to air source heat pumps. The second type use deeper geothermal heat directly without heat pumps. For Example, In the United States,, the Department of Energy refers to this technology as "Deep Direct Use" to differentiate such systems from the more common "exchange" systems.

This paper posits a third solution: a geothermal SuperCOP system with distinctly different design parameters and benefits compared to either of these primary types.

1.1 Modeling Objectives and Approach

To calculate the efficacy of a geothermal system with SuperCOP heat pumps, staff at Cornell University working under a grant from the U.S. Department of Energy (USDOE) developed a model (MEnU, for "Modeling Energy Use") that couples variable geothermal resources to a modeled campus generation, distribution, and building heating network (district energy system). The objective of this model was to quantify the heat extracted from local geothermal resources (subsurface fluids) over the course of each year based on actual building heat load (magnitude and variation), temperature requirements, and distribution mechanics. The resulting energy benefit, summed over the year from hourly calculations, allowed a more accurate assessment of the economics for Cornell's proposed geothermal project ("Earth Source Heat") than could be obtained using only simpler, broader assumptions.

Researchers used detailed Cornell system data to build, verify, and validate the model. MEnU includes various proposed system assets including heat pumps. MEnU incorporates building-by-building hourly breakdowns of heat use over a full calendar year to model the effect of both seasonal operations as well as future efficacy based on thermal improvements to buildings (individually or in sets) planned over time.

Cornell researchers also met with European geothermal specialists from various countries (Iceland, Germany, England, Finland, and France) to discern the experience of others in practical aspects of utilizing geothermal heat. During a visit in Paris, France with experts from ENGIE, Cornell staff witnessed a working model of a district energy system that was achieving significant GHG reductions using a low temperature (~60ºC) geothermal system that incorporated a heat pump asset in a manner similar to that modeled for the Cornell study.

1.2 Organization of this Paper

The remainder of this paper is arranged in four sections. Section 2 provides theoretical background on heat pumps and their application to geothermal direct heating systems (or similar sources). Section 3 details modeling efforts completed by Cornell to plan their geothermal project. Section 4 provides real-world information on the use an integrated "SuperCOP" heat pump for a working district energy system in the Dogger Basin developed by ENGIE. Section 5 provides summary conclusions, design guidance, and suggestions for additional research and application work related to geothermal system heat pump integration.

2. SUPERCOP HEAT PUMPS FOR DEEP GEOTHERMAL SYSTEMS OF MODERATE TEMPERATURES

Stand-alone geothermal systems (systems with only geothermal assets) are challenged in many regions to provide sufficiently hot temperatures to serve all the customer needs within a diverse district energy system. Operators of such systems are only able to guarantee flow and temperature that matches what is "naturally" available from the geothermal system; additionally, if system needs or resources vary over time or if future needs are uncertain, the geothermal development may need oversizing to ensure operations over a given contract period. The addition of a heat pump can provide the following benefits:

- Provide an operational "tool" to improve temperature and/or guarantee a minimum temperature.
- Improve sales by increasing the geothermal heat extraction per cycle by removing heat from the return loop (before returning the fluid to the subsurface) and adding that heat (plus the energy from the electrical input) to the supply loop.
- Allow operators to modify the system over time. Modifications may help in any of the following cases:
    - Geothermal temperature or flow drops over time
    - Customer needs change (or customers are added or removed)
    - Seasonal needs vary

Multi-asset district heating systems (systems that include other heating assets such as storage or non-geothermal heat-producing units) can significantly benefit from the integration of heat pumps. For multi-asset systems, if the geothermal system is arranged to be the first heating asset, it can supply heat into the return loop – where lower temperatures allow greater heat transfer (i.e., improved use of the geothermal resource). Figure 1 shows schematically this integration using Cornell as the example.

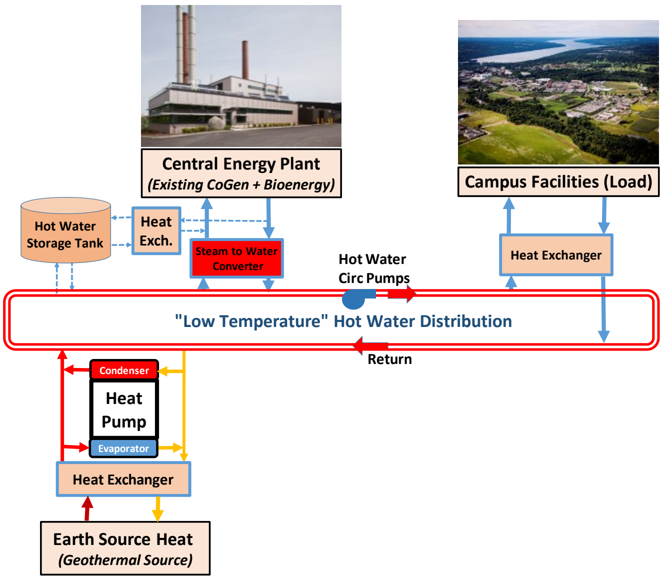

Figure 1: Conceptual Integration of Geothermal Source (Earth Source Heat). Geothermal heat is added to the system prior to the central plant and storage in multi-asset system to maximize heat transfer. An integrated central heat pump is modeled for this multi-asset system.

2.1 Coefficient of Performance (COP): Thermodynamic Limits and Real-world Performance

Cornell's review of available data confirmed the basic thermodynamic principals of heat pumps: their efficiency is dictated in large part by temperatures, as predicted by the Carnot theorem for an ideal heat engine. To quantify performance, we use the metric Coefficient of Performance (COP), which is defined as the heat added at the output (useful energy addition) divided by the required input energy to drive the mechanical refrigeration cycle:

$COP = Q_{out}/E_{in}$ (Equation 1.1)

Q_{out} is the total energy (heat) provided and E_{in} is the total electrical input

For a heat engine, the "ideal" or "Carnot" COP is as follows:

$COP = T_H/(T_H-T_L)$ (Equation 1.2)

In Equation 1.2, T_H and T_L are the high resulting temperature of the "hot side" fluid and the temperature (after heat extraction) on the "cold" side of the heat pump, respectively.

For a real system, inefficiencies are always present; we can express this as follows:

$COP = n^* \text{ COP Carnot} = n^* T_H/(T_H-T_L)$ (Equation 1.3)

In equation 1.3, n = efficiency

From a review of available industry data, Cornell found that for a broad range of applications and operating temperatures, heat pumps are available with n ~ 0.42 (i.e., the typical efficiency of a heat pump is about 42% of the ideal case). While better performances are possible (and reported), our study assumed available equipment will just meet this goal over a broad range, and therefore we used the following throughout:

$COP = 0.42^* T_H/(T_H-T_L)$ (Equation 1.4)

Using this reasonable approximation allows modeling across a broad range of applications without model-specific curves or similar data for each application.

2.1.1 Comparison of SuperCOPs to Ground Source and Air Source Heat Pumps (GSHPs and ASHPs)

Table 1 provides a comparison of the COP that would be achieved by a heat pump operating to produce water at a temperature suitable for wide-scale distribution (80°C). Table 1 simply uses equation 1.4 and assumes a single-stage heat pump for all cases.

Table 1: Sample COPs for air source, ground source, and SuperCOP heat pump systems

Heat Pump Type	**Assumed T_H requirement**	**Typical Winter Heat Source**	**Typical Heat Source (Exit) Temp T_L**	**COP**
Air Source HP	80°C	Ambient Air	-10°C	1.6
Ground Source HP	80°C	Ground Temp	10°C	2.1
Geothermal SuperCOP	80°C	Deep Earth/Aquifer	40°C	3.7

The calculated COP of 3.7 in Table 1 means that a geothermal SuperCOP heat pump will use *less than half* of the input energy (electricity) as an air source heat pump under these sample conditions to generate the same output heat energy.

2.1.2 Using Series (or Multi-stage) Units to Improve COP

These same thermodynamic equations also demonstrate that COPs can be improved further by operating units in series using a counter-flow arrangement. For example, a single heat pump (or heat pumps in parallel) as generally illustrated in Figure 2 can be designed to move heat from a cooler return fluid stream to a geothermally-sourced supply to provide additional output heat. To reduce the temperature difference across each heat pump and improve performance, multiple units in series (Figure 3) can accomplish this same goal.

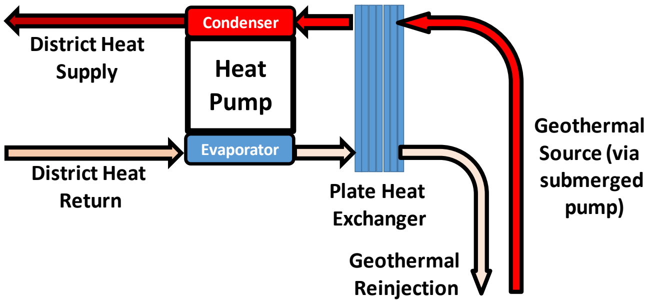

Figure 2: Simple schematic of a single-stage heat pump used to boost a geothermal source fluid temp for distribution into a district hot water supply system.

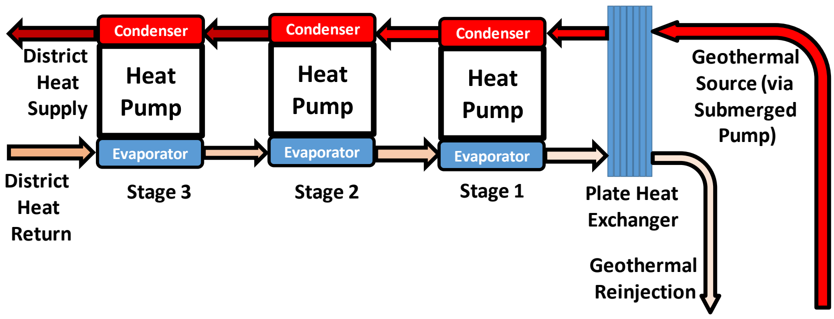

Figure 3: Schematic of three heat pumps placed in series to boost a geothermal source fluid temp for distribution into a district hot water supply system.

Figures 2 and 3 show examples of arrangements with a single heat pump and three heat pumps arranged in series, respectively. Table 2 provides the resulting COP values attainable by each system. This example assumes a geothermal source of 72°C and a target distribution temperature of 82°C. The “return flow” stream in this example starts at about 48°C.

Table 2: COPs for single stage versus multi-stage heat pump systems

Stage	T_H Target	Heat Source (Exit) Temp T_L	COP
Single Stage Only	82°C	41°C	**3.6**
Multi-Stage			
Stage 1	75°C	40°C	4.2
Stage 2	79°C	43°C	4.1
Stage 3	82°C	45°C	4.0
Overall (3 stages)			**4.1**

Table 2 shows an improved COP for the three-stage example that reduces electrical use by more than 10%. However, further COP improvements can be achieved through a well-planned design.

<u>2.1.3 Achieving Higher COPs in a Multi-asset System</u>

For a multi-asset system (i.e., a distribution that includes both geothermal and other conventional higher-temp heating inputs), incorporating geothermal as the first input on the return loop can reduce the temperature demands on the heat pump (require less work) and allow for higher COPs for this system. Table 3 shows the results of one case where the heat source (return water) temperature starts at about 48°C and the target is reduced to 78°C.

Table 3: COP Improvements for injection at lower temperatures as “initial asset”

Stage	T_H Target	Heat Source (Exit) Temp T_L	COP
Single Stage Only	78°C	43°C	**4.21**
Multi-Stage			
Stage 1	74°C	42°C	4.55
Stage 2	76°C	44°C	4.62
Stage 3	78°C	46°C	4.61
Overall (3 stages)			**4.59**

This system arrangement is still more efficient, needing only 1 unit of electricity to deliver about 4.6 units of heat.

The arrangement of the flows to and from the heat pump exchange elements may also be critical to optimize performance. Consider the case at Cornell, where delivery temperature of about 72ºC from a shallow "target" reservoir was estimated, but 80ºC was desired to serve a set of buildings (without extensive building improvements). An output temperature of 82ºC was targeted to accommodate distribution and transfer losses. Initially, the return temperature of our district heating system would be about 48ºC and the goals was to extract additional heat from that return loop (inject colder water into the formation) to reap a greater benefit from the finite geothermal pumping rate.

Two possible arrangements of "staged central" heat pumps are possible, as shown schematically in Figure 3 (previously used) and Figure 4. Both provide possible means to move heat from one subsystem to another to produce the primary goal: higher supply loop temperatures and lower re-injection temperatures.

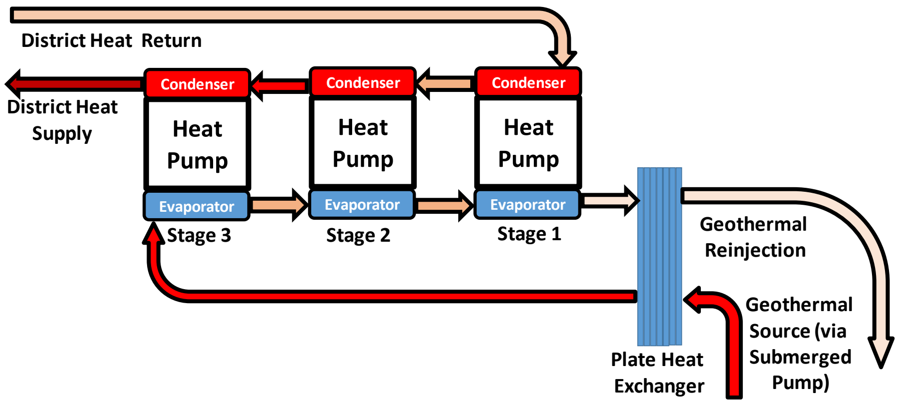

Figure 4: Like Figure 3, this schematic shows three heat pumps placed in series to boost a geothermal source fluid temp for distribution into a district hot water supply system; however, the piping arrangement is different to allow for higher performance for the design temperatures shown in Table 3.

The COPs are significantly different for these two arrangements. The arrangement in Figure 3, while efficient, requires more than 50% more electricity (COP = 4.1) that the arrangement in Figure 4 (COP = 7.0), even though the endpoint temperatures (82ºC to the district supply and ~40ºC to the heat exchanger for down-hole return) are approximately the same, as demonstrated in the table below (using equation 1.4 again). The difference in COPs make the return temperatures slightly different because less "waste" heat from electricity is involved.

Table 4: Example showing the importance of fluid paths for maximizing COP of heat pump systems

Arrangement and Stage	T_H Target	Heat Source (Exit) Temp T_L	COP
Figure 3 Arrangement			
Stage 1	75ºC	40ºC	4.2
Stage 2	79ºC	43ºC	4.1
Stage 3	82ºC	45ºC	4.0
1A Overall (3 stages)			**4.1**
Figure 4 Arrangement			
Stage 1	59ºC	39ºC	7.0
Stage 2	71ºC	50ºC	6.9
Stage 3	82ºC	61ºC	7.1
1B Overall (3 stages)			**7.0**

The improvements here are even more substantial. The actual temperatures of each geothermal and district system will change the values in each specific case; however, the principle of aligning heat pump flow arrangements to minimize (T_H – T_L) is an important design principle.

2. CORNELL MODELING EFFORT

Before turning to a discussion of actual field results (in Section 4) from ENGIE's operating system in the Dogger Basin, we provide more detail of the Cornell model used to quantify the potential for geothermal extraction from reservoirs underlying the campus in New York State and some primary modeling results.

Cornell facilities and academic personnel jointly developed their MEnU modeling tool (for "Modeling Energy Use"), a custom application that used standard Excel algorithms (and a few macros) for the purposes of assessing and optimizing the integration of geothermal energy into building heat infrastructure, using Cornell as an example.

MEnU was coupled to a subsurface resource model (Geophires). Geophires was initially developed at Cornell and further developed at the National Renewable Energy Laboratory (NREL). Together, these coupled models predict the economic viability ("Levelized Cost of Heat" or LCOH) for the predicted geothermal resources at the Cornell site. Another conference paper (*District Geothermal Heating Using EGS Technology to Meet Carbon Neutrality Goals: A Case Study of Earth Source Heat for the Cornell University Campus*) provides details on the subsurface model and the coupling of the two models. This paper focuses specifically on the MEnU (surface) model and even more specifically on the heat pump subroutines within that model.

Figure 5 shows how the system is integrated schematically.

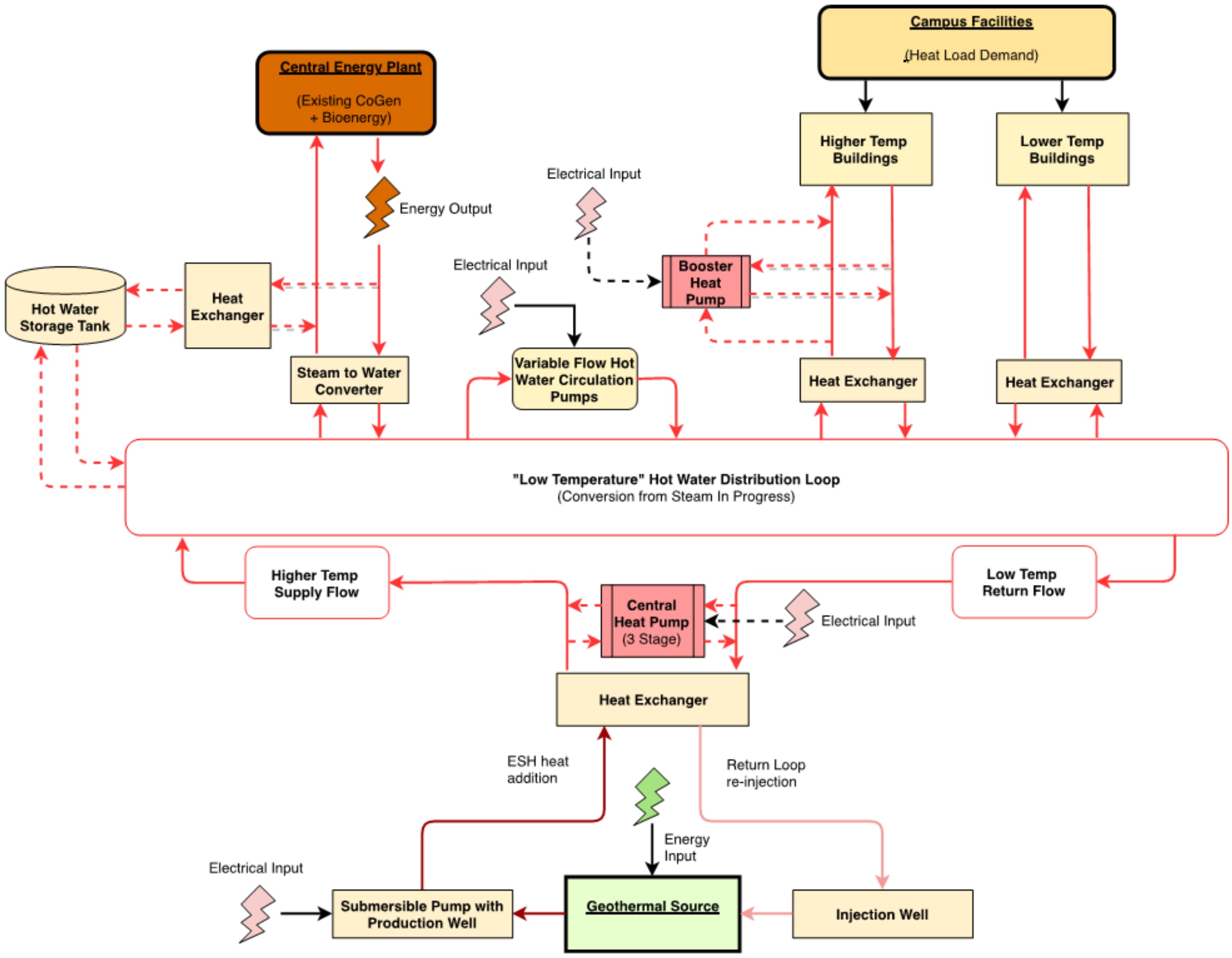

Figure 5: Schematic of Cornell's geothermal integration model (MEnU). A geothermal resource is the first energy input to the district heating loop, offsetting downstream fossil energy inputs at the Central Heating Plant to reduce GHG emissions.

The following are some key attributes of the MEnU model:

- Calculations are based on established heat transfer and thermodynamic equations (conservation of energy, heat transfer, etc.). Subject to operating assumptions and variables, the output values (heat extracted from the geothermal system; electrical power requirements, temperatures) are all mathematically derived, not theoretical approximations, for the given conditions.
- Earth Source Heat (Cornell's name for its geothermal source) is the first heating asset for Cornell's proposed multi-asset future heating system. The existing Cornell Central Heating Plant, located downstream, supplies additional heat using other assets (storage, biomass boilers, natural gas boilers, solar thermal, etc.).
- All heat exchange between heat supply units and the distribution system (Earth Source Heat, Central Heating Plant, Storage, Heat pumps) occurs across plate-and-frame heat exchangers sized for a minimal "approach temperature".
- A "central" heat pump modeled as a three-unit staged system is part of the geothermal heat supply system. The ENGIE system described in the next Section of this paper also operates across three distinct stages (heat pumps in series).
- The model includes three separate facility types (representing "Campus Load"). The three facility types are each connected to the district heating loop by a heat exchanger and each represent buildings with different temperature requirements.

- The model assumes variable distribution flow (controlled by an algorithm linked to hourly heat load) through the district heating (hot water) loop.

2.1 Heat Pumps in MEnU

Heat pump operations are explicitly modeled within MEnU using the realistic performance values (n = 0.42) described earlier in this paper. MEnU was also useful to inform the appropriate arrangement and placement of "centrally located" heat pumps in our system, which is the focus of this paper.

Building-level heat pumps, conversely, can allow designs with reduced temperatures in the primary hot water distribution loop of existing mixed-temperature systems, since building level heat pumps can "boost" temperature as needed in select areas. To minimize operating and capital costs, heat pumps are selected and controlled to minimize capacity and electrical requirements. Building-level heat pumps may also be an important asset for systems with diverse building energy needs. This paper, however, focuses on "centrally located" heat pump systems similar to the ones operating in the Dogger Basin system described in a later section.

2.2 Integrating Geothermal Energy into the District Heat System

Cornell uses substantial heat year-round (summer usage mostly for domestic hot water and cooling system reheat). Modeling shows that the system can utilize a modest geothermal resource year-round; preliminary modeling shows a capacity factor of over 90% for the first well set studied in the DOE project. Also, Cornell owns and operates other central resources, including the most efficient campus district cooling system in the U.S. (Lake Source Cooling) and a combined heat and power (CHP) plant, which today provides Cornell's power and coproduced steam for district heating. Both Lake Source Cooling and the CHP will remain at least until the ESH is fully proven, whereby the CHP will serve as a supplement and backup for the ESH system whereas hot water storage and other renewables may be integrated over time.

2.3 Sample Modeling Results

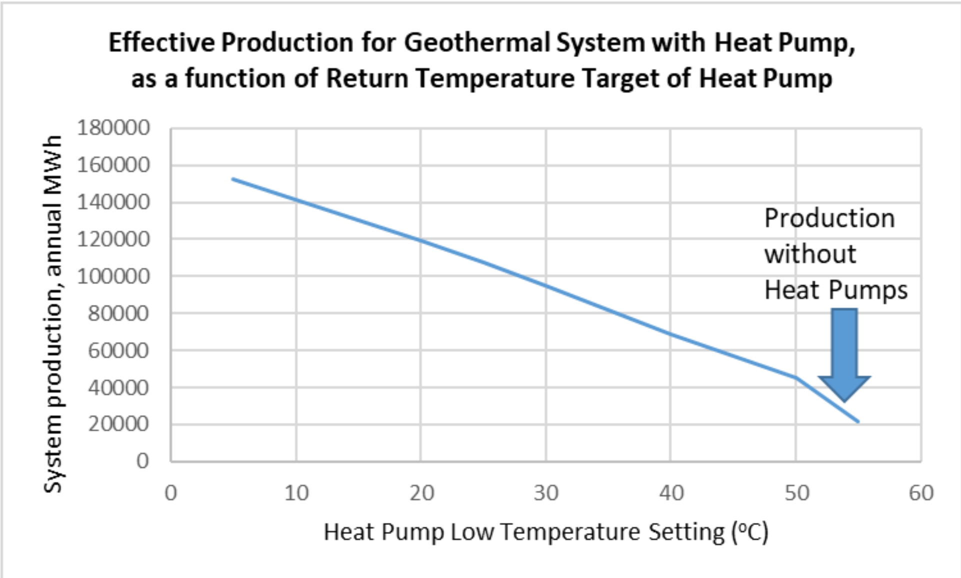

Figure 6: SuperCOP system effective COP as a function of heat pump return temperature.

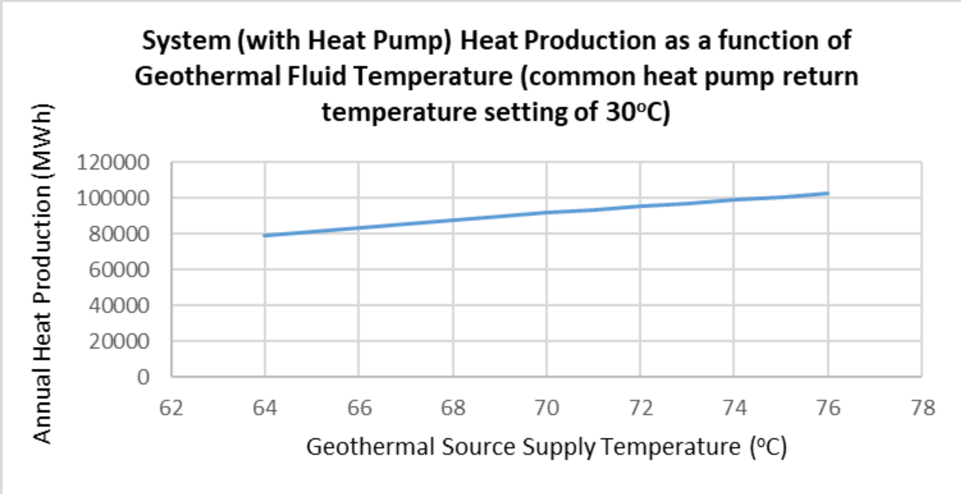

Figure 7: SuperCOP system heat production as a function of geothermal fluid temperature.

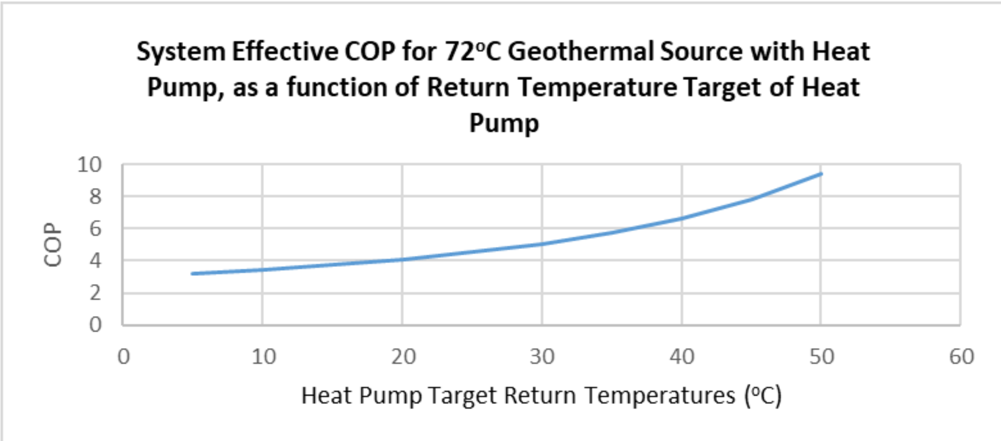

Figure 8: SuperCOP system effective COP as a function of heat pump return temperature.

Cornell modeling results are illustrative of the results obtained for a relatively low (72°C) predicted reservoir temperature with 50 kg/s flow. Figures 6 and 7 provide some representative results that show the addition of heat pumps can significantly improve the heat extracted from the geothermal resource and how variation in heat pump operations can also result in variations in the produced energy. In this example, heat pump are essential to making this system viable for the conditions modeled.

Figure 8 reminds us that there is still an optimization at play, namely, that our choice of heat pump operating conditions (in this case, re-injection set-point temperature) can significantly affect the overall Coefficient of Performance (COP), changing the ratio of heat delivered to input electrical energy. System COP is critical to overall greenhouse gas (GHG) mitigation impacts, as will be seen later in this paper.

These modeling results help Cornell predict initial electrical and equipment needs based on predictions of subsurface temperatures and fluid flow rates over a wide range. Modeling can also help plan for the potential of reservoir changes over time. The Geophires model for the Cornell site predicted temperature changes within the first thirty years of reservoir life that, although not substantial, were significant enough to impact economics. However, the use of a heat pump substantially mitigates this risk by allowing the system to provide essentially the same energy input over time – although additional electricity is needed as geothermal temperature lower to provide the same output energy.

Figures 6 and 7 demonstrate how integration of heat pumps can address the concern over reservoir changes with time. Specifically, Figure 6 shows the relatively small impact reservoir temperature can have on an integrated system, whereas Figure 7 shows the large energy impacts of changes in heat pump setpoints (albeit at lower COP, as suggested in Figure 8). This ability to use heat pumps to correct for reservoir changes over time may be an invaluable asset to a system owner looking to reduce risk in development of a low-temperature geothermal system.

3. GEOTHERMAL POTENTIAL: RESULT OF AN OPERATING SYSTEM

Underneath the "Ile de France Region" which surrounds Paris, there is a great opportunity to capture geothermal potential thanks to the presence of an aquifer called the Dogger. As depicted in Figure 9, the expected temperature of hot water varies quite significantly depending on locations within the Dogger Aquifer. The town of Rosny and surrounding areas are located on the east side of the Parisian Basin where the expected temperature at the top of the Dogger Aquifer is around 60°C.

The entity "Ygeo" was created to provide heating to this area with a multi-asset system integrated with renewable geothermal energy to meet the main goal of de-carbonization set forth by the cities. Since the district includes residential buildings, the system needed to meet the supply temperature required at the radiators (emitters) of those buildings. For most of the circa 1980s buildings, the supply temperature required by existing building systems during peak demand days is as high as 90°C, and returned fluid is also at relatively high temperatures (usually above 50ºC). Since the local temperature of the aquifer was only about 60ºC, heat pumps were included to boost the supply temperature. To provide the most efficient operation, the heat pumps were designed to improve the discharge temperature from about 60ºC to about 77ºC at peak, sufficient for many applications. Fossil fuel boilers in the network then provided higher temperature heat addition for the buildings with highest temperature needs, similar to the modeled Cornell arrangement.

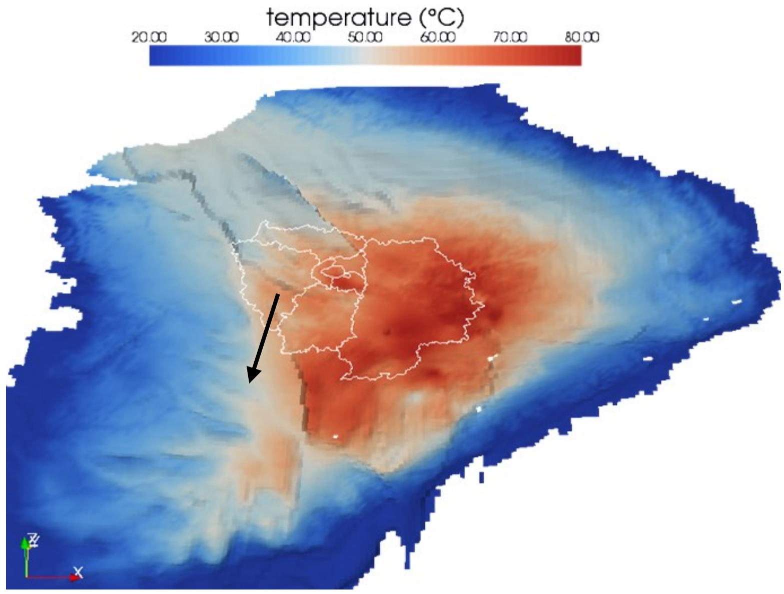

Figure 9: Expected temperature of hot water of the Dogger Aquifer.

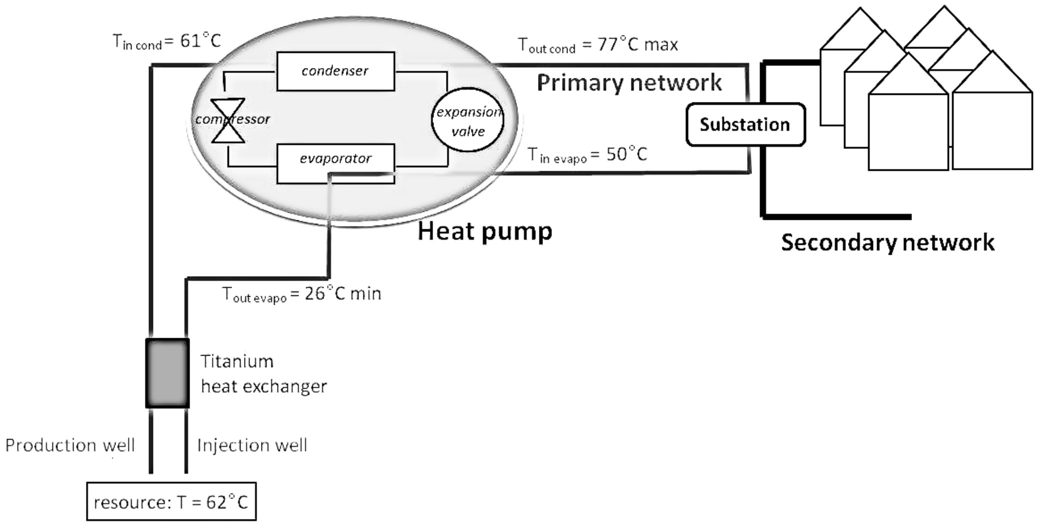

Figure 10: Schematic showing the basic layout and design goals of the system serving Rosny-sous-Bois community.

Figure 10 is a schematic of this system and Figure 11 shows an area view. Placing the heat pumps downstream of the primary system heat exchanger made it possible to increase the geothermal heat production significantly. In this configuration, the heat pumps also reduce the temperature of the re-injected fluids (by transferring heat from the return to the supply) and thus greatly improve the amount of heat removed from the ground. Without heat pumps, the re-injection temperature would be limited to the district energy return temperature, which during some seasons was above 50ºC and was never below about 47ºC. Because the heat pump could reduce the temperature to as low as 28ºC, it could **more than double** the heat extracted from the well (creating a delta T of almost 32ºC instead of the maximum of 13ºC that the district system created). This innovation allowed the system to surpass its design goal of displacing 60% of the district heat (previously provided by gas boilers) with renewable energy in the District Energy System's energy mix efficiently and at a very competitive price.

This application addresses a common difficulty when applying geothermal energy to an existing district system, namely, that the return temperature from the secondary network depends on the needs and design of clients' equipment (radiators and heating coils) which are not generally optimized for low-temperature geothermal energy. The return temperature dictates the temperature of the fluid re-entering the heat pumps at the evaporators, and thus the efficiency of the whole system. Thus, optimization of the heat pumps' characteristics regarding the resource temperature and the nature of radiators, while seeking for the lowest possible temperature reinjected in the aquifer (usually required by regulation) is a necessary design effort to maximize geothermal (and both environmental and economic) potential.

Heat pumps (or heat recovery chillers) can also be used for simultaneous heating and cooling, a powerful application that can offer high effective COPs for many users when operated with simultaneous heating and cooling loads. However, that application is not covered in this paper, since heat pump cooling here is used instead to reduce re-injection fluid temperature (rather than supply loads) and the heat pumps for this application are generally not selected for the lower temperatures needed for district cooling.

The Rosny system, illustrated in Figure 11, is a classic multi-asset, multi-user system, which includes 35 Energy Transfer Stations; 10 km of distribution lines; an installed geothermal (with heat pumps) capacity of 16 MW; a 18 MW gas fired boiler for back-up, peak heat, and peak temperature supply; and 6 back-up (or peaking) gas boilers along the network. The network consists of multiple customers (residential, public buildings, private buildings, and military) constituting a 100 GWh annual system heat load with supply temperature needs that range from 60°C to a max of 90°C at peak load.

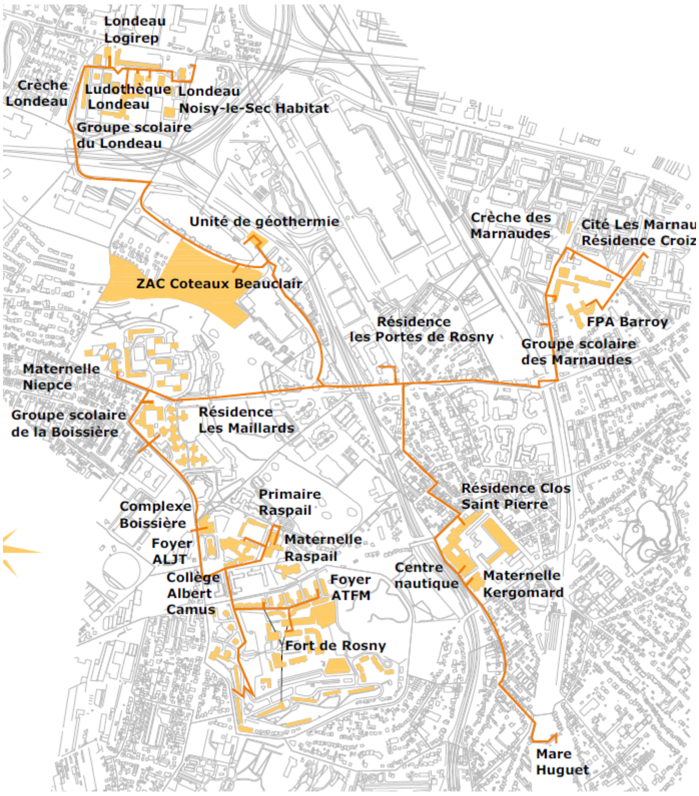

Figure 11: Plan view of the Rosny-sous-Bois Project (Dogger Basin, outside Paris).

Table 5: Overall expected performance values

Stage	HP	Component	Parameter	Unit	-7	-2	3	4	5	9	12	16
Stage HT	HP 1	Evaporator	INLET	°C	49,62	45,09	49,43	51,18	52,74	45,37	45,64	35,00
			Outlet	°C	40,65	37,60	40,53	41,83	43,46	37,86	38,50	35,00
			Flow rate	l/s	48,6	48,6	48,6	48,6	48,6	48,6	48,6	40,7
			Pressure Drop	kPa	14	14	14	13	13	14	14	10
			Cooling caHPity	kW	1799,7	1507,3	1785,2	1875,2	1861,0	1509,2	1435,3	0,0
		Condensor	inlet	°C	66,92	62,71	66,80	68,45	69,42	64,97	65,98	70,00
			Oulet	°C	74,11	68,51	73,92	76,04	76,98	71,51	75,00	70,00
			Flow rate	l/s	76,9	76,8	76,9	76,9	76,9	69,84	48,8	41,0
			Pressure Drop	kPa	18	18	18	18	18	15	8	5
			Puissance chaud	kW	2269,0	1833,3	2247,9	2394,6	2386,5	1877,8	1810,6	0,0
		Compressor	Puissance absorbé	kW	473,58	329,04	466,90	524,06	530,35	372,03	378,92	0,00
Stage LT	HP 2	Evaporator	inlet	°C	40,65	37,60	40,53	41,83	43,46	37,86	38,50	35,00
			Outlet	°C	32,21	30,87	32,17	32,83	34,15	31,02	38,50	28,26
			Flow rate	l/s	48,4	48,5	48,4	48,4	48,4	48,5	48,5	40,7
			Pressure Drop	kPa	14	14	14	14	14	14	14	10
			Puissance Froid	kW	1695,5	1353,0	1678,7	1806,0	1865,0	1376,4	0,0	1140,7
		Condensor	Inlet	°C	60,33	57,52	60,20	61,28	62,03	59,06	65,98	61,37
			Outlet	°C	66,92	62,71	66,80	68,45	69,42	64,97	65,98	70,00
			Flow rate	l/s	76,6	76,6	76,6	76,6	76,6	69,6	48,8	40,8
			Pressure Drop	kPa	18	18	18	18	18	15	8	5
			Puissance chaud	kW	2080,2	1636,4	2079,8	2260,4	2332,3	1696,1	0,0	1449,6
		Compressor	Puissance absorbé	kW	410,01	285,67	404,17	457,81	470,86	322,18	0,00	311,43
	HP 3	Evaporator	Inlet	°C	32,21	30,87	32,17	32,83	34,15	31,02	38,50	28,26
			Outlet	°C	25,01	25,00	25,03	25,19	26,28	25,00	31,65	25,22
			Flow rate	l/s	48,3	48,4	48,3	48,3	48,2	48,4	48,5	40,6
			Pressure Drop	kPa	14	14	14	14	14	14	14	10
			Puissance Froid	kW	1446,2	1182,1	1434,8	1532,5	1578,3	1210,9	1377,6	513,8
		Condensor	Inlet	°C	54,63	52,98	54,56	55,20	55,77	53,85	57,50	57,50
			Outlet	°C	60,33	57,52	60,20	61,28	62,03	59,06	65,98	61,37
			Flow rate	l/s	76,4	76,4	76,4	76,4	76,4	69,4	48,6	40,7
			Pressure Drop	kPa	18	18	18	18	18	15	8	5
			Puissance chaud	kW	1795,9	1433,4	1779,5	1918,0	1973,1	1492,4	1698,4	649,6
		Compressor	Puissance absorbé	kW	352,32	253,16	347,23	388,23	397,75	283,55	323,51	137,16
Stage LT + HT	HP 1 + 2 + 3	Evaporator	Inlet	°C	49,62	45,09	49,43	51,18	52,74	45,37	45,64	35,00
			Outlet	°C	25,01	25,00	25,03	25,19	26,28	25,00	31,65	25,22
			Flow rate	l/s	48,6	48,6	48,6	48,6	48,6	48,6	48,6	40,7
			Pressure Drop	kPa	46	46	46	46	46	43	35	26
			Puissance Froid	kW	4941,4	4042,4	4898,7	5213,7	5304,3	4096,5	2812,8	1654,4
		Condensor	Inlet	°C	54,63	52,98	54,56	55,20	55,77	53,85	57,50	57,50
			Outlet	°C	74,11	68,51	73,92	76,04	76,98	71,51	75,00	70,00
			Flow rate	l/s	76,9	76,8	76,9	76,9	76,9	69,8	48,8	41,0
			Pressure Drop	kPa	54	54	54	54	54	45	23	16
			Puissance chaud	**kW**	6145,2	4903,1	6107,2	6573,0	6691,9	5066,2	3509,0	2099,2
		Compressor	Puissance absorbé	kW	1235,9	867,9	1218,3	1370,1	1398,9	977,8	702,4	448,6
		COP			4,972	5,650	5,013	4,797	4,784	5,181	4,996	4,680
		EER			3,998	4,658	4,021	3,805	3,792	4,190	4,004	3,688

These needs are adjusted based on weather; Table 5 provides some critical design data showing this stage-by-stage temperature increase and how that final temperatures vary during differing outside temperature conditions (different system loads).

Figure 12 provides a one-line schematic of the Rosny area's central geothermal plant equipment. Note that a total of six (6) industrial heat pumps are used, with two parallel sets of three in series. The heat pumps are piped with reverse flow to minimize the temperature difference between condenser and evaporator sides (as discussed in the modeling theory section) to improve overall COP. Each unit provides a sequential "boost" of temperature to the supply, drawing energy from the return (with the goal of reducing the re-injection temperature).

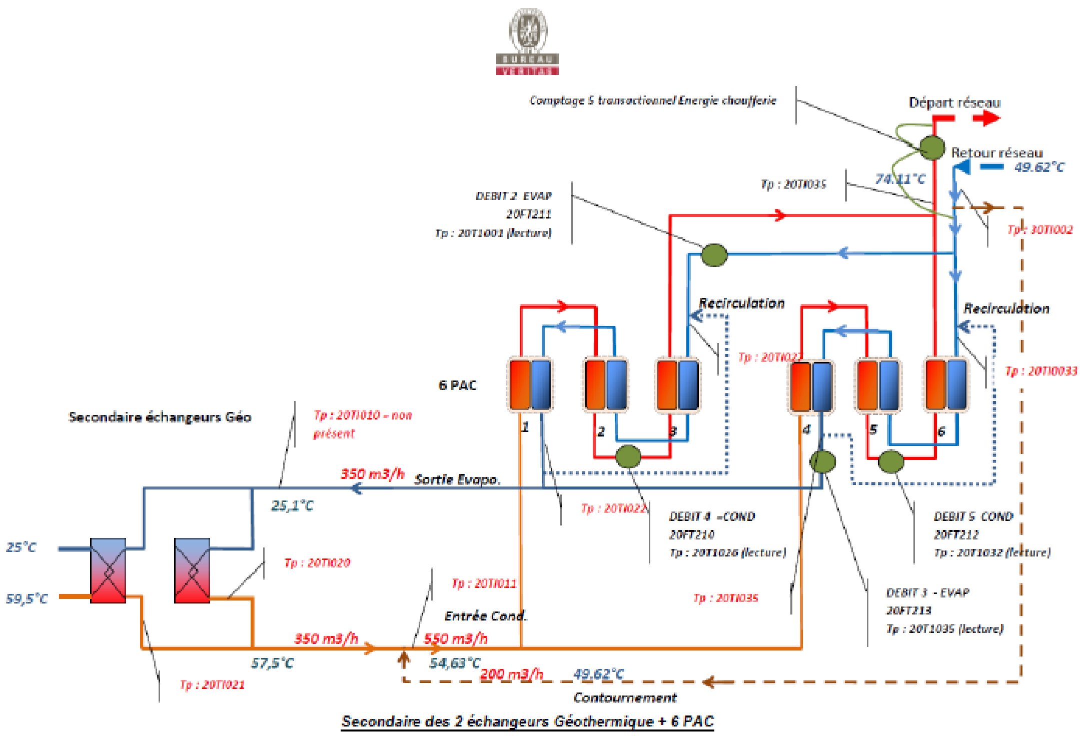

Figure 12: Design of the central plant combining heat pumps and geothermal production.

3.1 Overall Performance

The actual performance of the system is documented in Table 6. However, the full benefit provided by the heat pump may not be transparent in this table. Specifically, with a geothermal resource temperature of only about 60°C and an existing system not well designed for low temperature (i.e., with equipment needing higher temperatures and returning water at relatively high temperature), the Rosny application would be neither economically feasible nor as environmentally beneficial without heat pumps.

The geothermal resource at Rosny allows for a limited flow (320 m^3/h) of hot water at a temperature of around 60°C. To create an economical system, the reinjection temperature must be reduced as low as possible – in this case, as close as possible to the lowest authorized injection setting point of 26°C. The role of heat pumps is therefore to extract the calories remaining in the return lines network as much as possible, thus maximizing the overall geothermal production.

System sizing and design is complicated by temperature requirements and return temperatures that vary with system conditions (temperature and demands). However, an asset like a heat pump is of great value here, since it can be operated on demand and bypassed when not needed to save energy. Coupling that with bypass flows, as was modeled in the Cornell study and independently implemented in the Ygeo effort, can provide a high level of control to help optimize for the goals of high resource recovery, low electrical use, and maximum greenhouse gas (GHG) emissions reductions.

Table 6 reflects that controlling the return temperature of the network is necessary in order to be able to operate the geothermal plant optimally most of the time. As the table shows, during very cold weather, limitations in the system equipment may result in higher return temperatures, thus reducing the re-injection temperatures (reducing potential energy recovery). This observation led to a specific design change: the implementation of a system flow bypass. The bypass flow allowed the two evaporators and condensers flows to be decoupled from the HPs. This decoupling mode allowed for the extraction of the calories remaining in the return loop and a decrease of the reinjection temperature at the limit allowed by the law.

Different levels of control are available on the plant, including temperature and bypass flow setpoints, variable flow, and similar control features. Generally, water flow rate in the HPs (evaporator side and therefore geothermal) and central flow pass mainly through the condensers. The plant pilot also defines the central flow temperature setpoint and limits the geothermal injection temperature. Depending on the flow rate and the central flow setpoint temperature, two modes of operation are possible:

a. Mode 1 ("Heating"): No full optimization of the geothermal resource; Heat Pumps must reach the output temperature setting point at the condensers outlet

b. Mode 2 ("Geothermal Optimization" or "Cooling"): Full optimization of the geothermal potential; HPs are operated to meet the injection temperature limit allowed.

Table 6: Initial system design assumptions and water flow

	Réseau	Centrale géothermique			
Température extérieure	Puissance appelée par le réseau	T° retour réseau	T° entré géo	T° départ réseau	Débit géothermique
°C	kW	°C	°C	°C	m3/h
-7	39541,8	49,62	36,80	76,38	320
-6	38174,4	48,36	35,77	76,13	320
-5	36799,1	47,41	34,63	76,38	320
-4	35415,8	46,26	33,70	76,13	320
-3	34024,4	45,45	33,11	75,88	320
-2	32624,8	45,09	32,87	75,75	320
-1	31217,0	43,78	31,78	75,50	320
0	29800,9	42,92	31,14	75,25	320
1	28376,5	41,62	30,07	75,00	320
2	26943,6	40,80	29,47	74,75	320
3	25502,1	40,34	29,11	74,63	320
4	24052,1	39,15	28,26	74,24	320
5	22593,5	38,20	27,53	73,98	320
6	21126,0	37,05	26,62	73,72	320
7	19649,8	36,10	26,00	73,33	320
8	18164,6	35,72	26,00	72,88	320
9	16670,4	34,49	26,00	71,43	320
10	15167,2	33,64	26,00	70,36	320
11	13654,8	32,44	26,00	68,91	319
12	12133,2	31,85	26,00	68,19	287
13	10602,3	31,39	26,00	67,62	252
14	9061,9	30,80	26,00	66,91	216
15	7512,1	30,04	26,00	65,98	180
16	5952,7	30,44	30,44	61,00	167
17	4383,5	31,73	31,73	61,00	129
18	3120,9	52,00	52,00	61,00	298

Figure 13 shows the resulting anticipated system operating conditions as a function of overall system demand. This logic was aimed at operating the HPs to achieve highest possible load rate and HP efficiency.

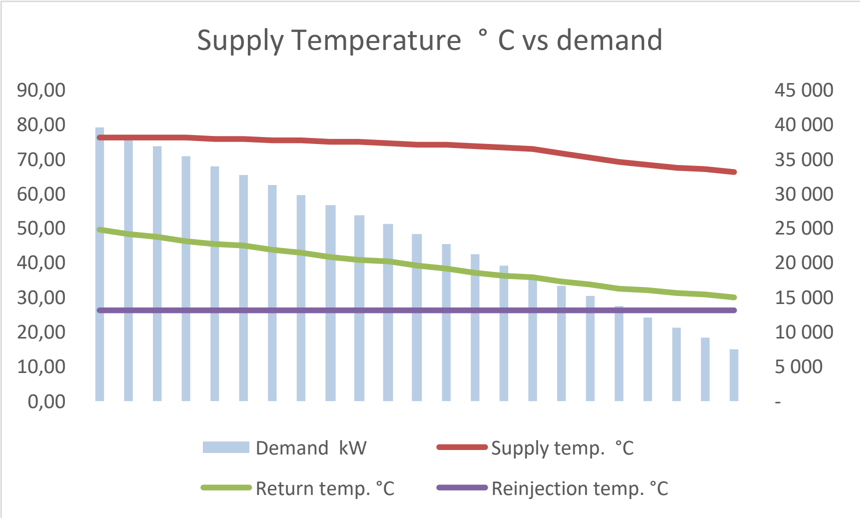

Figure 13: Design for the central plant. Values on the right axis represent kW demand; the left axis is temperature in °C.

Table 7 summarizes performance over one year. The challenge of matching production to useable energy creates some lost value but the efficient operation of the heat pumps minimizes these losses. The ability to vary the operation of the heat pumps is key to this optimization. Figure 14 shows the actual temperature records of geothermal supply, geothermal plant delivery, district heating system return, and re-injection temperatures. Note that the effective geothermal resource value is more than doubled by the inclusion of the heat pumps.

Table 7: Overall production

Synthèse réseau (system summary)	DJU (heating degree days)	Ventes chauffage (heat sales) MWh$_{th}$	Ventes ECS (other energy sales) MWh$_{th}$	Ventes totales (total sales) MWh$_{th}$	Production MWh$_{th}$	Rendement distribution (percent utilized) %
January	311	7,968	416	8,384	9,143	92%
February	389	8,561	496	9,057	9,810	92%
March	431	10,082	544	10,626	11,753	90%
April	146	3,696	321	4,017	4,430	91%
May	139	2,278	381	2,659	3,259	82%
June	0	729	259	988	1,209	82%
July	0	446	210	656	962	68%
August	0	543	229	772	1,034	75%
September	0	536	235	771	1,057	73%
October	105	1,398	330	1,728	2,250	77%
November	353	8,371	439	8,810	9,359	94%
December	258	7,445	410	7,855	9,247	85%
TOTAL	**2,132**	**52,054**	**4,270**	**56,325**	**63,514**	**89%**

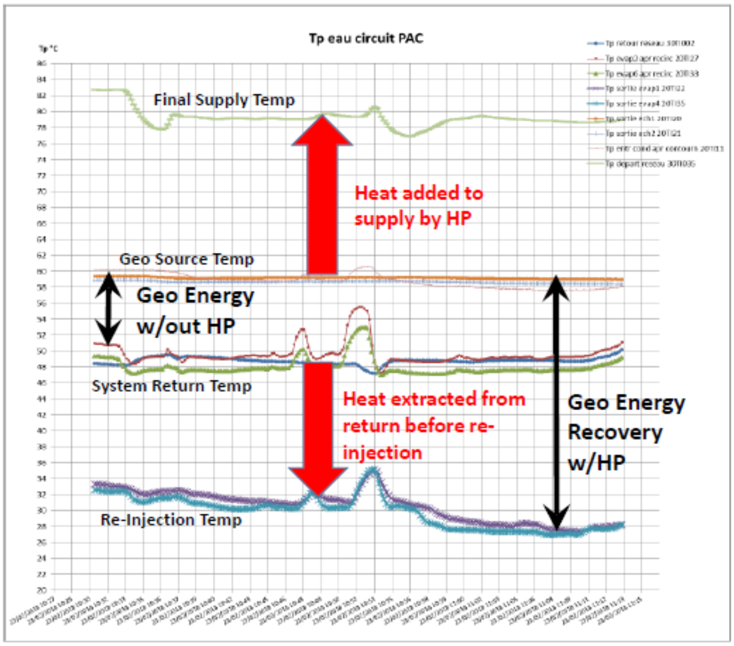

Figure 14: Recorded temperature curves and inferred heat pump performance improvement.

4. ENVIRONMENTAL BENEFITS AND TRADE-OFFS

Heat pumps can increase the range and potential of geothermal heating systems. The net impact on the environment is more nuanced.

Heat pumps use refrigerants, many of which are potent GHG gases and/or environmental toxins. The environmental impact of refrigerants is small if refrigerants are managed so that there is little or no leakage; while that is not always the case, centrally installed units are generally easier to manage since the central plant typically will have dedicated staff. Additionally, heat pumps that use CO_2 or other non-GHG fluids as refrigerants are being developed to eliminate or significantly reduce this area of impact.

Heat pumps require electricity for operation, so it is important to take into consideration the source of the electricity when assessing the overall environmental impact of using heat pumps. In Iceland and a few other places where essentially all electricity is generated through renewable or non-fossil sources (geothermal, hydropower, nuclear), electricity is not equated with GHG emissions (although electricity is still limited and may have other development impacts, so using less is still a goal). However, for most of the world, fossil fuels generate significant electricity, with electrification resulting in overall GHG production. This is true even in places like New York State, where the grid GHG emissions rates are relatively low (due to significant hydropower and nuclear power totaling more than half of the grid electricity) but natural gas is effectively always the marginal electrical source (i.e. the fuel used to provide electrical power for loads added or subtracted).

Moreover, for heating, heat pumps are most needed during seasons of low sunlight and in early hours when light is also low. Since solar PV is not commonly available and hydropower is not generally at peak in mid-winter, marginal electrical energy supply during (at least) peak heating hours will provided by some form of fossil fuel in most locations. Assuming 2.5 to 3 units of fossil energy are needed to create and deliver one unit of electricity and modern fossil heating systems are about 90% efficient, it would only be environmentally beneficial to use a heat pump for heating if the COP is higher than about 2.2 to 2.6.

4.1 Margin Emissions Rates and Relationship to COP

If a local Margin Emission Rate (MER) is known, the GHG impact of a heat pump can be compared to the GHG impact of fossil fuel combustion. For example, the MER in the region around Ithaca, NY (home to Cornell) is estimated at ~0.51 metric tons $CO_{2(eq)}$ per MWh. For the campus, the production of heat using a natural gas furnace or boiler that is 90% efficient versus a heat pump is compared in Table 9.

Table 8: GHG emissions (Metric tons CO_2 per $MW_{thermal}$ heat production)

90% efficient Furnace or Boiler	System with Effective COP of:					
	1.5	2.0	2.5	3.0	5.0	7.0
0.20	**0.34**	**0.25**	**0.20**	**0.17**	**0.10**	**0.07**

Table 8 suggests a heat pump must achieve a COP of 2.5 or higher to provide any environmental benefit over heating using a furnace, based on Cornell's local MER. Since COP depends on temperature, it follows that only with appropriate temperature endpoints can typical heat pumps provide GHG reductions. For areas where marginal emissions rates are higher (for example, an area that uses oil or coal for marginal power production), a heat pump with a higher COP may be needed to provide reliable GHG reductions. Conversely, where renewable electricity represents all or a part of the marginal load, electricity has lower GHG emissions and heat pumps with lower COPs may be sufficient to reduce GHG emissions overall. One concern about widespread

ASHP or GSHP deployment is that during the peak loads (coldest periods), the regional power requirements would likely be high enough that marginal power sources may be exclusively fossil-driven in most locations for the foreseeable future.

4.2 Comparison of Greenhouse Gas (GHG) Emissions for Specific Cases

To illustrate the importance of temperatures on GHG reductions with geothermal systems that integrate heat pumps and on the importance of applying marginal grid emission factors to understand impacts, we use conditions representative of Ithaca, NY and specific results of our modeling based on Cornell loads and facilities.

Figures 15 and 16 show that SuperCOP heat pumps generally can provide additional GHG reductions in addition to operating range and flexibility. However, utilizing a heat pump beyond its range of highest efficiency (i.e., aiming temperatures that are too high on the supply side or too low on the return) provides operational benefits but may not always optimize GHG reduction.

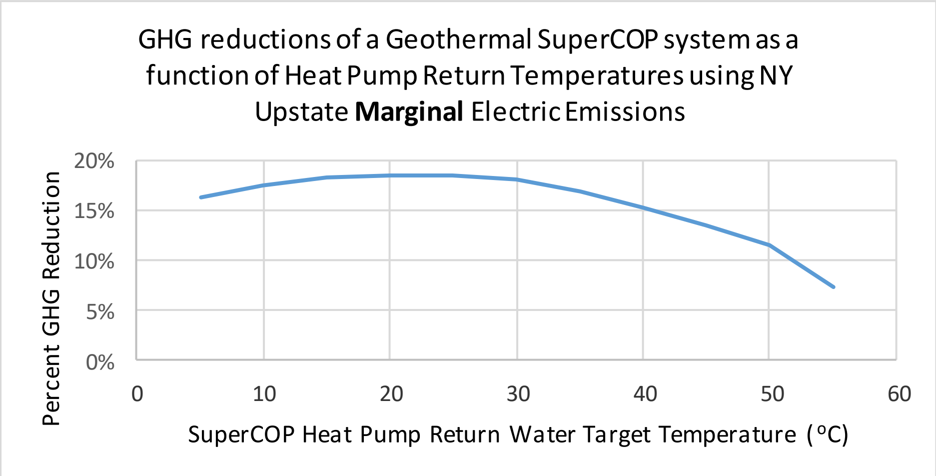

Figure 15: Potential GHG Emission Reductions based on NYS Marginal Emission Factors for a single Well-Pair at Cornell.

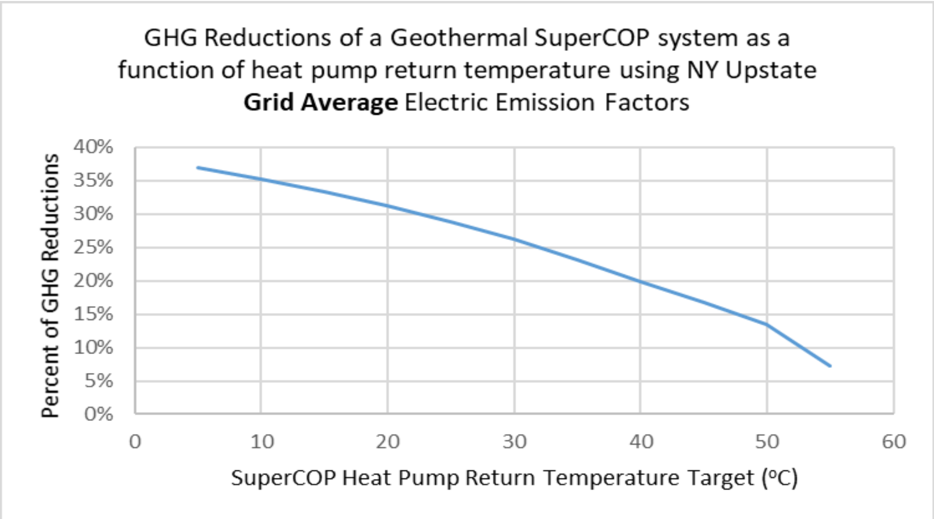

Figure 16: GHG Emission Reductions based on NYS Average Grid Emission Factors for Single Well Pair at Cornell.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Modeling studies and operating data demonstrate the benefits of heat pumps integrated into district heating systems that use geothermal resources. Specifically, a properly integrated heat pump optimized for temperatures can add the following benefits to multi-asset systems:

- Reduce overall Greenhouse Gas (GHG) emissions.
- Extract significant additional heat from a geothermal well pair, adding value without increasing drilling, pumping, or subsurface piping costs.
- Facilitate district heating system operations. An operator with the additional asset of a heat pump can expand the heat flow "on demand" and smooth operations in response to district system demands and usage on a real-time basis.

- Adjust to changing subsurface conditions over the life of the system. A heat pump can reduce a common risk to geothermal development: the potential for degradation of temperature or flow over time.

- Adjust to changing surface infrastructure over the life of the system. Similarly, a heat pump can allow a district heat distribution system with non-optimal design of heat delivery to provide improved performance until building heat delivery design issues are improved over time, or to "boost" the heat provision should additional loads be added.

- Enable lower temperature geothermal integration into typical district energy systems without extensive district improvements.

- Expand the possibilities for the economical use of geothermal resources. The Cornell study found that there was not a single, finite Levelized Cost of Heat (LCOH) for a given geothermal resource; rather, optimized building/facility demand design parameters allowed for a series of LCOH values corresponding to different GHG reduction potentials.

To further optimize the potential for such systems, the following research and development efforts are suggested:

- More research and sharing of knowledge regarding the design limitations and performance of large-scale higher temperature heat pumps suitable for SuperCOP applications. Most commercial chiller systems are not designed to use higher temperature source and target water systems. Significant research and development is underway utilizing a wide range of refrigerants (including those with low GHG impacts). Yet, the industry is just starting to make commercial equipment available for temperatures hot enough for district heating systems and publishing operating data that is sufficient and broad enough to allow engineers to select such equipment with confidence in its final performance. More of this work is necessary to advance the application of "SuperCOP" systems.

- Variable water flow data for heat pumps. Modeling and field experience suggest a high potential for expanded heat pump integration using variable water flow rates on the two sides (condenser and evaporator) of the heat pump. Testing these models in working systems (and publishing the data) would help verify these potentials.

- Continued research and demonstration of effective low temperature heating systems. As heat pumps in general become more prevalent, lower temperature building heating systems are becoming more common. However, many mechanical design engineers still lack the familiarity and experience with these systems, and in some markets, it is difficult to find appropriate heat transfer equipment for use in buildings that work under lower temperatures. Continuing development and education of designers and manufacturers is key to expanding this application; until that expertise develops, Owners must be careful to select firms with the right experience and knowledge to ensure a positive outcome.