

CLOSED-LOOP GEOTHERMAL AND HEAT PUMP SYSTEMSTechnical Field

[0001] This disclosure relates to geothermal systems and methods.

Background

[0002] Geothermal systems utilize heat from within the earth for surface heat distribution, electricity production or for other applications. Some geothermal systems employ a geothermal working fluid that is injected into a closed loop of wellbores drilled into the subterranean zone. The geothermal working fluid can be recovered after it absorbs heat from the subterranean zone.

[0003] Heat pump systems transfer heat from one location to another using a refrigerant fluid. A typical mechanical heat pump system, for example, consists of an evaporator, compressor, condenser, and expansion valve. The refrigerant absorbs heat in the evaporator, is compressed by the compressor, releases heat in the condenser, and is de-pressurized across the expansion valve. This allows heat pumps to efficiently provide heating or cooling by moving heat rather than (for example) generating it.

Summary

[0004] This disclosure relates to geothermal energy production.

[0005] Certain aspects of the subject matter herein can be implemented as a method. The method includes determining a specified demand as a function of time of thermal energy from a heat exchanger of a heat pump. The heat pump configured to transfer thermal energy to the heat exchanger from a geothermal working fluid circulating in a closed-loop geothermal well. The closed-loop geothermal well includes a first surface wellbore extending from a terranean surface to a geothermal subterranean zone, a second surface wellbore extending from the terranean surface to the geothermal subterranean zone, and plurality of connecting wellbores connecting the first surface wellbore to the second surface wellbore. The method further includes controlling a heat output from the heat exchanger to meet the specified demand. The controlling is at least in part by adjusting at least one of a flow rate or inlet temperature of the geothermal working fluid in the closed-loop geothermal well.

[0006] An aspect combinable with any of the other aspects can include the following features. The thermal energy from the heat exchanger can provide a first portion of thermal energy provided to a heat distribution system. The method can further comprise providing a second portion of thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid and not via the heat pump.

[0007] An aspect combinable with any of the other aspects can include the following features. The thermal energy from the geothermal working fluid transferred by the heat pump can comprise a first portion of thermal energy from the geothermal working fluid, and further comprising generating electricity using a second portion of thermal energy from the geothermal working fluid.

[0008] An aspect combinable with any of the other aspects can include the following features. The flowing of working fluid in the closed loop geothermal systems can be via thermosiphon.

[0009] An aspect combinable with any of the other aspects can include the following features. The flowing of the geothermal working fluid in the closed loop geothermal systems can be driven at least in part by a circulation pump.

[0010] An aspect combinable with any of the other aspects can include the following features. The heat pump can be a mechanical heat pump.

[0011] An aspect combinable with any of the other aspects can include the following features. The heat pump can be an absorption or adsorption heat pump.

[0012] An aspect combinable with any of the other aspects can include the following features. The specified demand is an annual peak demand and is greater than 1 megawatt.

[0013] Certain aspects of the subject matter herein can be implemented as a method including determining a specified target heat output to a district heat network based at least in part on forecasted electricity or heat prices. The method further includes controlling operations of a closed-loop geothermal well to meet the target heat output by controlling the heat output from the heat exchanger of a heat pump. The closed-loop geothermal well includes a first surface wellbore extending from a terranean surface to a geothermal subterranean zone, a second surface wellbore extending from the terranean surface to the geothermal subterranean zone, and plurality of connecting wellbores connecting the first surface wellbore to the second surface wellbore. The heat pump is configured to transfer thermal energy to the heat exchanger from a geothermal working fluid circulating in a closed-loop geothermal well. The controlling the heat pump is at least in part by adjusting the flowrate and/or inlet temperature of the geothermal working fluid in the closed-loop geothermal well.

[0014] An aspect combinable with any of the other aspects can include the following features. The target heat output can be based in part on at least one of net cash flow and forecasted heat and electricity prices as a function of time.

[0015] An aspect combinable with any of the other aspects can include the following features. The flowing of working fluid in the closed loop geothermal systems can be via thermosiphon.

[0016] An aspect combinable with any of the other aspects can include the following features. The flowing of the geothermal working fluid in the closed loop geothermal systems can be supported in part by a circulation pump.

[0017] An aspect combinable with any of the other aspects can include the following features. The thermal energy from the heat exchanger can provides a first portion of thermal energy provided to a heat distribution system. The method can further include

providing a second portion of thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid and not via the heat pump.

[0018] An aspect combinable with any of the other aspects can include the following features. The heat pump can be a mechanical heat pump.

[0019] An aspect combinable with any of the other aspects can include the following features. The heat pump can be an absorption or adsorption heat pump.

[0020] An aspect combinable with any of the other aspects can include the following features. The thermal energy from an electrical resistance heater can provide a portion of the thermal energy to a heat distribution system. The method can further include providing a second portion of the thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid of the closed loop geothermal system and transferred by the heat pump with the distribution of thermal energy provided between these systems can be determined in part based on forecasted electricity and heat prices.

[0021] An aspect combinable with any of the other aspects can include the following features. A forecast horizon can be less than 72 hours.

[0022] An aspect combinable with any of the other aspects can include the following features. Operating the closed-loop geothermal system can be in a dispatchable manner with charge and discharge cycles.

[0023] An aspect combinable with any of the other aspects can include the following features. The thermal energy from the geothermal working fluid transferred by the heat pump can include a first portion of thermal energy from the geothermal working fluid. The method can further include generating electricity using a second portion of thermal energy from the geothermal working fluid.

[0024] An aspect combinable with any of the other aspects can include the following features. The specified demand is an annual peak demand and is greater than 1 megawatt.

Brief Description of Drawings

[0025] FIG. 1 is a graphical illustration of heat demand at a city-wide scale over the course of a year in accordance with the concepts herein.

[0026] FIG. 2A is a schematic side cross-sectional view of an example closed-loop geothermal system in accordance with the concepts herein.

[0027] FIG. 2B is a schematic side cross-section view of another example closed-loop geothermal system in accordance with the concepts herein.

[0028] FIG. 2C is a schematic side cross-section view of another example closed-loop geothermal system in accordance with the concepts herein.

[0029] FIG. 3 is a schematic illustration of a heat pump system fed by a geothermal working fluid circulating in a closed-loop geothermal system in accordance with the concepts herein.

[0030] FIG. 4 is a graphical illustration of a coefficient of performance as a function of desired heat temperature in accordance with the concepts herein.

[0031] FIG. 5 is a graphical illustration of thermal output as a function of flow rate of a geothermal working fluid circulating in a closed-loop geothermal system in accordance with the concepts herein.

[0032] FIG. 6 is a graphical illustration of a coefficient of performance as a function of desired heat temperature in accordance with the concepts herein.

[0033] FIG. 7 is a graphical illustration of optimal closed-loop geothermal and heat pump system capacity for three different electricity prices and a constant heat price.

[0034] FIG. 8. is a graphical illustration of a coefficient of performance as a function of thermal output at a condenser of different systems in accordance with the concepts herein.

[0035] FIG. 9 is a graphical illustration thermal demand with a variable intra-day electricity price.

[0036] FIG. 10 is a schematic illustration of electrical resistance heater and a combined heat pump and closed-loop geothermal system operating in parallel.

[0037] FIG. 11 illustrates a “cascade configuration” in which the geothermal working fluid of the closed-loop geothermal system pre-heats the heat distribution fluid before entering the heat pump evaporator.

[0038] FIG. 12 shows a cascade configuration similar to FIG. 11 but reversed.

[0039] FIG. 13 is a schematic illustration of a combined closed-loop geothermal plus heat pump can be configured to include combined heat and power modes, prioritizing heat sales with the remaining heat diverted to an organic Rankine cycle plant to generate electrical power

[0040] FIG. 14 is an illustration of an example on how heat from the geothermal working fluid in the configuration shown in FIG. 10 can be distributed

DETAILED DESCRIPTION

[0041] The production of medium temperature grade heat and steam (considered here to be between 100-400°C) can be challenging to decarbonize. Low theoretical maximum heat efficiencies and engineering challenges with current heat pump systems can limit the use of ambient temperature heat sources to produce this grade of heat from heat pump systems.

[0042] In closed-loop geothermal systems, a geothermal working fluid is circulated within a closed loop that includes a subsurface well and a surface facility. The geothermal working fluid is heated by the Earth surrounding the well, and then circulated to the surface, where the surface facility extracts heat from the geothermal working fluid. In certain instances, the facility includes a heat exchanger for extracting heat and conveying that heat into a related process such as a Rankine cycle (e.g., organic Rankine Cycle) or other heat cycle that generates electricity, a district heating plant, a steam generation process, or another process. In certain instances, the process directly uses the heated geothermal working fluid, such as by passing it through an expander (e.g., a turbine) that drives an electric generator or directly using the heat of the geothermal working fluid in an industrial, agricultural or residential process. In closed-loop systems, the primary heat transfer is conductive between the geothermal working fluid and the Earth (rock) surrounding the well. Therefore, the well is sealed to prevent (entirely or substantially) contact between the geothermal working fluid and the natural fluids in the formation (for example, groundwater).

[0043] Heat production in closed-loop geothermal systems can in some instances be limited by subsurface temperatures. If rock temperatures exceed the desired process temperatures, methods to bring these high temperatures to the surface include increasing the inlet temperature and/or reducing the geothermal working fluid circulation rate. A disadvantage of both of these approaches is that they reduce the thermal output of the closed-loop, and therefore the potential revenue from heat sales for a given closed-loop system. In other words, the same capital expenditure can be used to construct the loop but

with a reduced thermal output with high temperature production. High outlet temperatures may be required (further reducing the thermal output of the system) if, for example, the desired process heat is in the form of steam (rather than liquid pressured water), to provide the latent heat energy to convert liquid water into steam.

[0044] Outside providing baseload heat, a solution is needed to provide flexible/dispatchable heat generation to meet the daily and seasonal variations in heat demand throughout the year. A closed-loop geothermal system may be unable to economically store thermal energy subsurface on a seasonal timescale, and dispatchable operation may be efficient only on an intra-day cycle. Because a significant portion of the cost of a closed-loop geothermal system may be capital expenditure, with a low marginal cost of generation, it may be necessary to operate the system at a near 100% capacity factor to be economic.

[0045] In contrast to closed-loop geothermal systems, heat pump systems can incur a majority of their total costs as operating expenses, primarily attributed to the expenditure on electricity. For example, if electricity prices are €100 / MWhe (megawatt hour electric), and the heat pump COP is 2.5, the cost of heat (negating the capital cost of the heat pump and other operating costs) is roughly $\text{€}100 / \text{MWhe} / 2.5 = \text{€}40 / \text{MWhth}$ (megawatt hour thermal). This makes the unit economics of using heat pumps very sensitive to power prices. Due to the high marginal cost of generation, heat pumps can be utilized at low-capacity factors (often less than 50%), providing flexible/dispatchable heat generation.

[0046] In addition to efficiency challenges, there may be engineering limitations to the design of heat pump systems, mostly concentrated around the compressor. Some off-the-shelf heat pumps are limited to a temperature lift of $<100^{\circ}\text{C}$. In general, higher temperature lifts require high compression ratios, resulting in multistage compressor designs, complex engineering, and high costs due to the extreme conditions (high compressor pressure ratios). For this reason, it is rare to see heat pumps that can deliver heat at temperatures $>120^{\circ}\text{C}$ (using ambient temperature heat sources). To provide higher temperatures (needed for industrial use and/or steam generation) a higher temperature heat source is needed (which often is not available or accessible).

[0047] Heat distribution networks (such as district heating networks) have demand profiles that can be correlated to ambient temperatures. The hours of the day with lowest

ambient temperatures of the year correspond to the hours with the highest thermal heat demand. Most networks have some baseload thermal requirement needed for hot water heating and other uses. FIG. 1 is a graphical illustration of district heat demand for an example medium sized European city (30MWth baseload demand and 210MWth peak demand). Providing flexible/dispatchable heat generation to meet the heat demand throughout the year can be challenging.

[0048] In contrast to applications using small scale heat pumps used in individual homes/businesses (which may use, for example, small ground-source heat pumps), larger heat distribution networks designed to provide heat on a district scale or for industrial use (typically >1 megawatt (thermal) (MWth) annual peak demand) may require substantially higher input temperatures when ambient temperatures are lowest (highest heat demand coincides with the highest lift temperature). If the heat pump is fed by a heat source influenced by ambient conditions (water, air etc.), this can result in the lowest system efficiencies during peak demand.

[0049] FIG. 2A shows an example closed-loop geothermal system 100 in schematic, side cross-sectional view in accordance with the concepts herein. In certain instances, the closed-loop geothermal wellbore system can be, for example, a system such as that developed by Eavor Technologies Inc. of Calgary, Alberta, which includes a network of sealed lateral wellbores that exchange heat with the subterranean zone. A closed loop system as shown in FIGS. 2A - 2C -- including multiple lateral wellbores connecting inlet and outlet surface wellbores - can provide a greater surface area for thermal transfer from the geothermal zone 204 than other closed-loop systems (for example, a pipe-in-pipe system). A multilateral closed loop system design can improve capital efficiency of the closed loop system as there is no need for casing, liners and/or cement for the vast majority of the well, eliminating a substantial consumable in the well construction process. When combined with a heat pump system, a multilateral closed loop system enables a broader range for selecting inlet temperature and flow rate, due to a stronger thermosiphon effect, which significantly reduces or even eliminates the parasitic load of a circulation pump relative to other closed loop systems. In addition, a multilateral closed loop system can have a larger subsurface volume and residence time of the geothermal working fluid,

thereby enhancing the system's energy storage capacity, which is beneficial for dispatchable operation.

[0050] System 200 includes a geothermal well 202 drilled into the Earth through a geothermal subterranean zone of interest 204. In certain instances, the subterranean zone is a formation, portion of formation or multiple formations having little to no naturally occurring fluids. In certain instances, the formation can be impermeable or substantially impermeable (for example, 0.1 millidarcies or less). In certain instances, the subterranean zone is in a basement formation. In certain instances, the rock of the subterranean zone is granite. In the illustrated instance, well 202 includes an inlet surface wellbore 220 and an outlet surface wellbore 230 in close proximity, each extending between the terranean surface and the subterranean zone 204. The inlet surface wellbore 220 and outlet surface wellbore 230 are connected within the subterranean zone 204 by one or more connecting wellbores 240. In the illustrated instance, connecting wellbores 240 define a multilateral pattern of wellbores, including a plurality of pairs of lateral wellbores 250, a subset of which are kicked off from the inlet wellbore 220 and a subset of which are kicked off from the outlet wellbore 230. The pairs of lateral wellbores 250 each intersect at a respective junction at or near their respective toes. Thus, the inlet wellbore 220, outlet wellbore 230 and connecting wellbores 240 define a closed loop.

[0051] The inlet wellbore 220 and the outlet wellbore 230 can be drilled from the same drilling pad and/or reside on the same well site. In certain instances, the wellbores 220, 230 are drilled within 10, 25, 50 or 100 meters of one another. In other instances, the inlet surface wellbore 220 and the outlet surface wellbore 230 can be separated by a longer distance. For example, FIG. 2B, discussed in more detail below, shows a configuration where the surface wellbores 220, 230 and the connecting wellbores 240 define a U-shape configuration. In certain instances, the inlet surface wellbore 220 and the outlet surface wellbore 230, when the geothermal well 202 is configured as a U-shape, are drilled 3,000 meters or more apart.

[0052] In the illustrated instance, inlet surface wellbore 220 and outlet surface wellbore 230 are vertical wellbores, drilled substantially straight (i.e., without the use of directional drilling methods or equipment). In other instances, one or both of the surface wellbores are other than vertical (e.g., slanted) and/or may be drilled with the use of

directional drilling techniques. The connecting wellbores 240 are drilled using directional drilling techniques through the surface wellbores 220, 230, and include a curve in their trajectory beginning at a kickoff 248 at surface wellbores 220, 230. Although shown as slanted downward, in some instances, some or all of the connecting wellbores are horizontal. In some instances, the connecting wellbores 240 follow the geological dip of the formation in the subterranean zone. In some instances, lateral wellbores 250 are anywhere from 2,000 meters to 10,000 meters or more in length and from 1,000 meters to 8,000 meters or more in depth from the surface. Typical wells may be deeper than 3000 meters in depth.

[0053] FIG. 2A shows each pair of lateral wellbores 250 parallel to one another extending in the same direction (azimuth) from their respective surface wellbore 220, 230. The lateral wellbores 250 extending from the inlet surface wellbore 220 are shown above the lateral wellbores 250 extending from the outlet surface wellbore 230. In some instances, the upper lateral wellbores 250 are directly above their (and are, in some instances, directly above a respective one of the lower lateral wellbores 250. In FIG. 2A the upper lateral wellbores 250 each turn to intersect its adjacent lower lateral wellbore 250 pair at the junction 254 to connect the surface wellbores 220, 230. In other instances, one or more of the lower lateral wellbores 250 could intersect the upper lateral wellbores 250. Regardless, the configuration of connecting wellbores 240, one set atop the other defines a stacked wellbore pattern, with one sub-pattern of wellbores above and one sub-pattern of wellbores below. In certain instances, one or more additional sets of stacked patterns can be drilled from the surface wellbores 220, 230 at different depths (i.e., with different kickoffs 248). In FIG. 2A, the lower lateral wellbores 250 extend past and below the junction 254 to define a sump 252. The sump 252 provides a location for debris to accumulate outside of the flow path through the wellbores. In other instances, one or more of the upper lateral wellbores 250 could extend past the junction to define the sump 252.

[0054] The connecting wellbores 240 of FIG. 2A slant downward; i.e., they have an inclination 270 from vertical. In some instances, some or all of the connecting wellbores can be horizontal (i.e., having an inclination 270 of about ninety degrees) or substantially horizontal. In some instances, as shown in FIG. 2B, connecting wellbores 240 can have a steeper slant; i.e., inclination 270 can be less than that shown in FIG. 1B, or vertical

(inclination 270 is zero) or substantially vertical. In some instances, connecting wellbores 240 follow the geological dip of the formation in the subterranean zone. In some instances, lateral wellbores 150 can have a length of 2,000 meters to 10,000 meters or more and can reach a depth of 1,000 meters to 8,000 meters or more.

[0055] FIG. 2C is another embodiment of a geothermal well system 200 having lateral wellbores 250 extending, respectively, from the inlet and outlet surface wellbores 220, 230 toward one another. The pairs of lateral wellbores 250, once intersected, together with the inlet and outlet wellbores 220, 230, define a generally U-shape. The configuration of connecting wellbores 240 defines a pattern of wellbores, in certain instances, in the same plane. In certain instances, one or more additional patterns of connecting wellbores can be drilled between the surface wellbores 220, 230 at different depths (i.e., with different kickoffs 248).

[0056] Referring to FIGS. 2A and 2B and 2C, collectively, in some instances, the surface wellbores 220, 230 are cased (at least partially or entirely), and the connecting wellbores 240, including the junctures at the kickoffs 248 are open hole (i.e., without casing or liner or a junction liner). In some instances, the connecting wellbores 240 can be at least partially lined (e.g., include a liner or casing in those portions where the subterranean zone 204 is fractured, susceptible to collapse, unconsolidated or otherwise needing a liner). The connecting wellbores 240, including the junctures to the inlet and outlet surface wellbores 220, 230 are sealed (entirely or substantially) with a sealant against exchange of fluids with the surrounding subterranean zone 204. In some instances, the sealant can be in the form of a fluid sealant (such as an alkali-silicate fluid) flowed through the wellbores. The sealant is designed such that all or substantially all of the geothermal working fluid circulated through the well 202 during operation is recovered to the surface, and no or little naturally occurring fluids from the subterranean zone 204 are recovered. In other words, the resulting well 202 is closed loop. In certain instances, the sealant can be applied to the wellbores during drilling the connecting wellbores 240, e.g., included in the drilling fluid and/or supplied in fluid slugs distinct from the drilling fluid. Alternatively or additionally, the sealant is applied after drilling and/or during operation of the well. In certain instances, the sealant can be included in the geothermal working fluid and/or supplied in fluid slugs, distinct from the geothermal working fluid.

[0057] In the illustrated instance, system 200 further includes a facility 210 disposed between inlet surface wellbore 220 and outlet surface wellbore 230. Well 202 can be sealed and a geothermal working fluid added to the closed loop and circulated in the system such that it absorbs heat from subterranean zone 204. In certain instances, facility 210 includes valves and pumps for controlling the flow of the geothermal working fluid through the well 202, as well as a heat exchanger for extracting the heat from the geothermal working fluid and conveying it into a related process, such as a Rankine cycle (e.g., Organic Rankine Cycle) or other heat cycle that generates electricity, a steam generation process for industrial, agricultural or residential use, or another process. In certain instances, instead of, or in addition to a heat exchanger, facility 210 directly uses the heated geothermal working fluid, such as by passing it through an expander (e.g., a turbine) that drives a electric generator or directly using the heat of the geothermal working fluid in an industrial, agricultural or residential process. In some instances, facility 210 is disposed at or near the Earth's surface; in other instances, facility 210 may be disposed partially or fully within a subsurface location. The facility 210 need not be housed in one location. For example, in some instances, it can be split between one or more discrete locations connected by piping.

[0058] Facility 210 in the illustrated instances includes a heat pump system 260, configured to extract heat from the geothermal working fluid as it circulates through the closed-loop system. As shown in FIG. 3, heat pump system 260 can include an evaporator 302, a compressor 304, a condenser 306 (operated by mechanical energy from, for example, an electrical source), and an expansion valve 308, through which a heat pump working fluid circulates. Heat pump system includes heat exchanger 310 to enable heat exchange from the geothermal working fluid to the heat pump working fluid, and heat exchanger 312 to enable heat exchange from the heat pump working fluid to a heat distribution system (such as a district heating network). As will be understood by those skilled in the art, the closed-loop geothermal system provides the heat energy that is upgraded by mechanical energy to a desired temperature needed for the heat demand ($Q_{\text{condenser}}$). In other words, the heat pump is the interface between the heat demand and the closed-loop geothermal system. This configuration has an advantage of eliminating interaction (and temperature constraints because of this interaction) between the closed-

loop geothermal system and the heat demand, providing maximal flexibility and optimization opportunity to improve system output.

[0059] The efficiency of heat pump system 260 can be expressed as a coefficient of performance (COP), which is defined by the following equation:

$$COP = \frac{Q_{condenser}}{Q_{electric}} \quad (1)$$

where $Q_{condenser}$ is the thermal output of the heat pump and $Q_{electric}$ is the electrical input to the compressor. The energy balance of the system can be expressed as follows:

$$Q_{condenser} = Q_{electric} + Q_{evaporator} \quad (2)$$

where $Q_{evaporator}$ is the heat absorbed by the evaporator. Heat pump COPs exceed 1, meaning more thermal energy is exchanged than electrical energy provided into the system. The 2nd law of thermodynamics limits the maximum COP of a heat pump as follows:

$$COP_{Carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}} = \frac{T_{hot}}{T_{lift}} \quad (3)$$

An approach using the Lorenz method can also be used to evaluate the COP with temperature glides. COPs achieved by commercial heat pump systems are typically up to 50-60% of the Lorenz/Carnot maximum COP. $T_{hot} - T_{cold}$ is referred to as the lift temperature required by the system: the larger the lift temperature, the lower the efficiency of the heat pump.

[0060] FIG. 4 is a graphical illustration of COP as a function of desired heat demand for a heat pump system in accordance with the concepts herein. More specifically, FIG. 4 illustrates an example of how COP changes with different desired heat temperature grades assuming 55% of Carnot COP. Generating 80°C heat from a constant 10°C heat source has a COP of ~2.8, vs 120°C with a COP of <2. Many heat distribution networks (especially older less efficient district heating networks) have a peak demand temperature requirement of $\geq 120^\circ\text{C}$. This COP change with desired temperatures also impacts the

carbon intensity of these systems, depending on the make-up of the electricity grid feeding into the heat pump.

[0061] FIG. 5 is a graphical illustration of thermal output as a function of flow rate of a geothermal working fluid circulating in a closed-loop geothermal system in accordance with the concepts herein. Two main variables can be manipulated: geothermal working fluid circulation rate and inlet temperature. Each corresponds to a thermal output (plotted on the y axis) and outlet temperature (not shown). Higher circulation rates and lower inlet temperatures can maximize the temperature difference between the geothermal working fluid and rock (and thus the thermal output) but can reduce outlet temperatures.

[0062] This interdependence between flowrate and inlet temperature on outlet temperature is unique to closed loop systems in general, such that there may be little or no increased cost to change the operating point of loop (outside of using a circulation pump for flowrates more than the maximum thermosiphon rate). FIG. 5 shows that thermal output of the loop can be increased by a factor of 2x or more simply by changing the operating point (e.g., 60°C inlet temperature and flowrate of 60 kg/s corresponds to a thermal output of 14MWth compared to an inlet temperature of 20°C and flowrate of 150kg/s where the thermal output is 28MWth). In systems with only a closed-loop geothermal system, the operating point of the loop can be fixed based on the required heat distribution system temperatures (i.e., inlet temperature is set by the heat distribution system return temperature (plus a small amount), and the outlet temperature is set by the required heat distribution system inlet temperature (plus a small amount)). This constraint does not apply for a combination closed-loop geothermal and heat pump system, improving system flexibility and providing additional optimization opportunities. In many cases the use of a circulation pump to maximize the heat extraction may be optimal for combination systems, and the lower temperature heat generated by the closed-loop geothermal system can be upgraded by the heat pump to the desired temperature.

[0063] FIG. 6 is a graphical illustration of a coefficient of performance as a function of desired heat temperature in accordance with the concepts herein, showing the COP advantage of using a closed-loop geothermal system. Plotted in blue is a “heat pump only” system relying on ambient temperature heat and two simplified closed-loop geothermal scenarios (modeled as an isothermal heat source), one producing 60°C heat

and another producing 100°C heat. The higher the source temperature, the higher the efficiency and reduced electricity consumption of the system. The closed-loop geothermal operation and heat pump design can be jointly optimized based on the desired heat demand, capital costs of the loop/heat pump and electricity prices (opex). For a given desired temperature, the closed-loop geothermal plus heat pump system can have double or more the COP of a comparable heat pump-only system (therefore half the CO₂ emissions and half the electricity consumption). The three production temperatures shown in FIG. 6 (120°C, 150°C and 200°C) are representative of peak heat distribution network temperatures, lower temperature/pressure steam generation, and higher temperature/pressure steam generation, respectively. The optimal capacity and system design is influenced in part by the forecasted price of electricity and heat price.

[0064] FIG. 7 presents the optimal closed-loop geothermal and heat pump system capacity for three different electricity prices and a constant heat price. The closed-loop geothermal system and geometry in all cases is identical, and thermal output of the closed loop geothermal system is adjusted by altering inlet temperature and flowrate. Each operating point of the closed loop geothermal system corresponds to a particular thermal input and temperature input to the evaporator of the heat pump, which also determines the total thermal output and the COP of the system. The dashed vertical lines represent the optimal system capacity that maximizes project cash flow after expenditure on electricity. The simplified example demonstrates that under lower electricity prices (\$50/MWh), the optimal system capacity increases to 48 MWth, in contrast to higher electricity price scenario (\$150/MWh), where the optimal system capacity decreases to 23 MWth. Adjustment of the operating point (closed loop geothermal inlet temperature and circulation rate) for a given system design to reduce electricity consumption for the heat pump system is unique to closed loop systems in general and provides system flexibility for implementation in regions with differing heat and electricity prices.

[0065] The ability to control outlet temperatures and thermal output of a closed-loop geothermal system such as that shown in FIGS. 2A and 2B can have an impact on the dispatchable capability with heat pump systems, as compared to traditional geothermal and traditional enhanced geothermal systems (EGS). Such systems can be less effective at controlling (or are unable to control) outlet temperatures and flowrates to the same

extent as is possible as the systems shown in FIGS. 2A and 2B. With the systems and methods disclosed herein, designed to a specification for the maximum heat demand, system efficiency can improve in off-design scenarios with joint control of the heat pump and geothermal working fluid circulation operating point. The temperature of the geothermal working fluid at the surface can be adjusted to match thermal demand and increase efficiency of the system. Reducing thermal output (via a lower circulation rate or higher inlet temperature) can result in higher working fluid outlet temperatures and therefore lower temperature lifts, higher COPs and lower electricity consumption.

[0066] FIG. 8 is a graphical illustration of a coefficient of performance as a function of thermal output at a condenser of different systems in accordance with the concepts herein. When matching the temperature profile of the heat source, a closed-loop geothermal system can provide (for example) $\sim 15\text{MWth}$. For any generation above this nominal capacity, the geothermal working fluid operating point is adjusted (to increase the circulation rate and/or reduce the temperature of the geothermal working fluid at the loop inlet), increasing the thermal output of the geothermal system but reducing the outlet temperature. The produced heat from the closed-loop geothermal system is upgraded with the heat pump to meet the temperature requirements of the heat demand. The maximum design capacity of the closed-loop geothermal plus heat pump system shown in FIG. 8 is 36MWth ($Q_{\text{condenser}}$), where the maximum temperature lift is required. This flexible operation can be most useful in applications where heat demand fluctuates on a seasonal timeframe. For example, for district heating networks in the winter the system can deliver 36MWth , in the summer the system can provide the baseload $\sim 15\text{MWth}$ from the closed-loop geothermal system alone, and the system can efficiently generate heat when demand lies between those two end points. A normal heat pump only system does not have the capability to adjust the temperature of the heat source (with varying demand), therefore COP is flat (negating off-design compressor and heat exchanger inefficiencies). Furthermore, the closed-loop geothermal system can be operated in a dispatchable manner to generate higher temperatures for certain batch processes or changing demand on an intra-day cycle, reducing the temperature lift requirement of the heat pump which can be desirable to reduce electricity consumption when forecasted electricity prices are high. Many industrial processes have large heat demand swings on the intra-day, and in

accordance with the concepts disclosed here, heat energy can be stored in the subsurface to reduce electricity consumption of the heat pump during peak hours.

[0067] In the example provided in FIG. 9, the thermal demand is flat (20MWth) and is satisfied by the systems described in FIGS. 2A - 2C, with a variable intra-day electricity price. Note that the combined closed loop geothermal and heat pump system can be configured to deliver heat across a wide range of intra-day fluctuations in power price, heat price and demand. Heat demand refers the heat pump thermal output at the condenser and closed loop geothermal system thermal output refers to the heat pump evaporator input. In accordance with the energy balance in eqn (2), the remaining energy is provided via electrical input to the heat pump. Often characterized by the term "duck curve", the variation in power prices resulting from the pronounced imbalance between electricity supply and demand trends, can result in substantial intra-day variation in electricity prices especially with increased penetration of intermittent renewable electricity generation. The dispatchable characteristics of the closed loop geothermal system can reduce the electricity expenditure for system and exploit intra-day electricity price variation. The closed loop geothermal system achieves dispatchable operation by storing energy sub-surface, slowing or stopping circulation of the geothermal working fluid by automated surface valve control, and thus increasing the residence time and heat uptake of the fluid, essentially charging the system. When required, this energy is discharged by increasing the circulation rate and quickly displacing this pre-heated fluid to surface. When electricity prices are low, the closed-loop geothermal system can be re-charged, and an increased portion of the total heat output is made up of electricity. During periods of elevated electricity prices, the charged fluid can be surfaced, thereby mitigating the electricity needed to fulfill a specific thermal demand.

[0068] In certain instances, as shown in FIG. 10, the heat demand can be satisfied with a system 1000 that combines an electrical resistance heater 1002 combined with heat pump system 260, operating in parallel. Electrical resistance heater 1002 converts electricity to power at a COP of ~ 1 , whereas the combined heat pump and closed loop geothermal system COP exceeds 1. During periods when the electricity price is low, the closed-loop geothermal system can be "switched-off" or the thermal output of the closed loop geothermal system can be reduced to charge the closed loop geothermal system with

a substantial portion or all of the thermal demand provided by the electrical resistance heater. When electricity prices increase, the closed loop geothermal system can be discharged and the thermal output of the resistance heater can be reduced or eliminated entirely.

[0069] FIG. 11 illustrates a “cascade configuration” 1100 in which the geothermal working fluid of the closed-loop geothermal system pre-heats the heat pump fluid (refrigerant) at a preheater heat exchanger 1102 before entering the heat pump evaporator. The evaporator reduces the inlet temperature of the geothermal working fluid, and this energy is used to upgrade the inlet temperature of the heat distribution network. This configuration has the advantage of reducing the geothermal working fluid inlet temperature, improving the temperature difference between the rock and geothermal working fluid, increasing thermal output of the closed-loop geothermal system. Note this configuration can have a lower COP due to the larger temperature lift between the geothermal working fluid inlet temperature and heat demand temperature requirement.

[0070] FIG. 12 shows a cascade configuration 1200 that is similar to configuration 1100 of FIG. 11 but reversed. The higher temperature geothermal working fluid outlet is used in the heat pump system first, resulting in higher heat pump COPs due to low temperature lifts. The leftover heat is used to preheat the heat pump return fluid at preheater 1202. This configuration has a higher heat pump COP, but a reduced system thermal output relative to the configuration of FIG. 8.

[0071] As shown in FIG. 13, a combined closed-loop geothermal plus heat pump plus organic Rankine cycle (ORC) configuration 1300 can include combined heat and power modes, prioritizing heat sales with the remaining heat diverted to an ORC plant to generate electrical power with a simple ORC and heat distribution heat exchanger system 1302. The ORC in this embodiment includes one or more turbines, evaporators, recuperators, pumps and air coolers to generate electricity from the closed loop geothermal heat source when heat demand is less than the baseload capacity of the closed loop geothermal system. The ORC can include a Rankine cycle or other heat cycle that generates electricity. The heat exchanger in 1302 transfers heat from the closed loop geothermal working fluid to the heat distribution network, without the use of a heat pump. In some instances, the heat for the heat distribution network can be siphoned from the ORC working fluid rather than

directly from the closed loop geothermal working fluid. The cooled geothermal working fluid is returned to the closed loop geothermal well. The advantage of this mode of operation is it prioritizes heat sales, which can be highly economic due to little or no conversion losses. In a scenario where the geothermal working fluid loop nominal capacity (without a heat pump) exceeds that of the baseload or minimum heat demand over the year, an ORC can be utilized to fully utilize the available heat from the geothermal working fluid and convert it to power.

[0072] FIG. 14 is a process flow diagram of an example method 1400 for how heat from the geothermal working fluid in the configuration shown in FIG. 10 can be distributed. For example, one can assume a 10MW baseload geothermal working fluid output that can generate the temperature profile desired by the heat demand. The method begins at step 1402 in which heat demand of the heat distribution system is determined to be greater or less than the baseload (for example, 10 MW). If demand is greater than the baseload 10MW then, at step 1404, the heat pump can be started (and operating point of the geothermal working fluid adjusted) such that all heat flow from the geothermal working fluid is diverted towards the heat pump. If at step 1402 it is determined that demand not greater than baseload and then at step 1406 it is determined that demand is exactly equal to the baseload (for example, 10MW) then, at step 1408, all heat flow from the geothermal working fluid can be diverted to the heat distribution exchanger. If at step 1406 it is determined that demand is less than baseload (for example, less than 10MW), then, at step 1410 part of the heat flow can be converted from the geothermal working fluid to the heat distribution exchanger and the remaining heat flowed to the ORC for electrical power production. (Note that the heat pump can be shut-down in the cases where heat demand is less than or equal to baseload (for example, $\leq 10\text{MW}$). In some instances with this configuration, no scenario may exist in which both the heat pump and ORC are operational at the same time. This configuration with a heat pump and an ORC may only be suitable if the baseload heat demand is below the nominal capacity of the closed-loop geothermal loop; otherwise, the geothermal working fluid loop alone or the geothermal working fluid loop plus the heat pump can be economically utilized.

[0073] In some instances, rather than employing a traditional heat pump with a compressor as presented in FIGS. 2A- 2C, 3, and 8-10, an absorption/adsorption cycle

heat pump can be used. In essence an absorption/adsorption heat pump takes the medium temperature heat provided by the geothermal working fluid and splits it into two streams, one high temperature and the other low temperature. The lack of mechanical compression in such systems can mean these cycles have substantially lower operating/electricity costs; however, the system efficiencies may be lower. COP can be defined for these cycles as: $\text{COP} = \frac{\text{Useful Thermal Output (high temperature)}}{\text{Thermal Input (medium temperature)}}$. The COP for these systems can be approximately 50%, meaning for every MW of geothermal working fluid thermal input, 0.5 MW of high temperature heat is generated. Because of this low thermal efficiency, the benefit of these systems can in some instances be marginal, and they may also be less technologically mature than traditional heat pumps. An absorption/adsorption system combined with a closed-loop geothermal system can also be configured in the reverse to produce a chilled stream that can be used for district cooling networks, with the geothermal working fluid acting as a heat sink.

What is claimed is:

1. A method, comprising:

determining a specified demand as a function of time of thermal energy from a heat exchanger of a heat pump, the heat pump configured to, transfer thermal energy to the heat exchanger from a geothermal working fluid circulating in a closed-loop geothermal well, the closed-loop geothermal well comprising:

a first surface wellbore extending from a terranean surface to a geothermal subterranean zone;

a second surface wellbore extending from the terranean surface to the geothermal subterranean zone; and

plurality of connecting wellbores connecting the first surface wellbore to the second surface wellbore; and

controlling a heat output from the heat exchanger to meet the specified demand, the controlling at least in part by adjusting at least one of a flow rate or inlet temperature of the geothermal working fluid in the closed-loop geothermal well.

2. The method of claim 1, wherein the thermal energy from the heat exchanger provides a first portion of thermal energy provided to a heat distribution system, and further comprising providing a second portion of thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid and not via the heat pump.

3. The method of claims 1 or 2, wherein the thermal energy from the geothermal working fluid transferred by the heat pump comprises a first portion of thermal energy from the geothermal working fluid, and further comprising generating electricity using a second portion of thermal energy from the geothermal working fluid.

4. The method of any of claims 1 to 3, wherein the flowing of working fluid in the closed loop geothermal systems is via thermosiphon.
5. The method of any of claims 1 to 4, wherein the flowing of the geothermal working fluid in the closed loop geothermal systems is driven at least in part by a circulation pump.
6. The method of any of claims 1 to 5, wherein the heat pump is a mechanical heat pump.
7. The method of any of claims 1 to 6, wherein the heat pump is an absorption or adsorption heat pump.
8. The method of any of claims 1-7, wherein the specified demand is an annual peak demand and is at least 1 megawatt thermal.
9. A method, comprising:
 - determining a specified target heat output to a heat distribution system based at least in part on forecasted electricity or heat prices; and
 - controlling operations of closed-loop geothermal well to meet the target heat output by controlling the heat output from the heat exchanger of a heat pump, the heat pump configured to transfer thermal energy to the heat exchanger from a geothermal working fluid circulating in a closed-loop geothermal well, the closed-loop geothermal well comprising:

a first surface wellbore extending from a terranean surface to a geothermal subterranean zone;

a second surface wellbore extending from the terranean surface to the geothermal subterranean zone; and

plurality of connecting wellbores connecting the first surface wellbore to the second surface wellbore, wherein the controlling the heat output is at least in part by adjusting the flowrate and/or inlet temperature of the geothermal working fluid in the closed-loop geothermal well.

10. The method of claim 9, wherein the target heat output is based in part on at least one of net cash flow and forecasted heat and electricity prices as a function of time.

11. The method of claim 9 or 10, wherein the flowing of working fluid in the closed loop geothermal systems is via thermosiphon.

12. The method of any of claims 9 to 11, wherein the flowing of the geothermal working fluid in the closed loop geothermal systems is supported in part by a circulation pump.

13. The method of any of claims 9 to 12, wherein the thermal energy from the heat exchanger provides a first portion of thermal energy provided to a heat distribution system, and further comprising providing a second portion of thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid and not via the heat pump.

14. The method of any of claims 9 to 13, wherein the heat pump is a mechanical heat pump.

15. The method of any of claims 9 to 14, wherein the heat pump is an absorption or adsorption heat pump.

16. The method of any of claims 9 to 15, wherein the thermal energy from an electrical resistance heater provides a portion of the thermal energy to a heat distribution system, and further comprising providing a second portion of the thermal energy to the heat distribution system with thermal energy extracted directly from the geothermal working fluid of the closed loop geothermal system and transferred by the heat pump with the distribution of thermal energy provided between these systems determined in part based on forecasted electricity and heat prices.

17. The method of claim 16, wherein a forecast horizon is less than 72 hours.

18. The method of claim 17, further comprising operating the closed-loop geothermal system in a dispatchable manner with charge and discharge cycles.

19. The method of any of claims 9 to 15, wherein the thermal energy from the geothermal working fluid transferred by the heat pump comprises a first portion of thermal energy from the geothermal working fluid, and further comprising generating electricity using a second portion of thermal energy from the geothermal working fluid.

20. The method of any of claims 9 to 15, wherein the specified demand is an annual peak demand and is at least 1 megawatt thermal.