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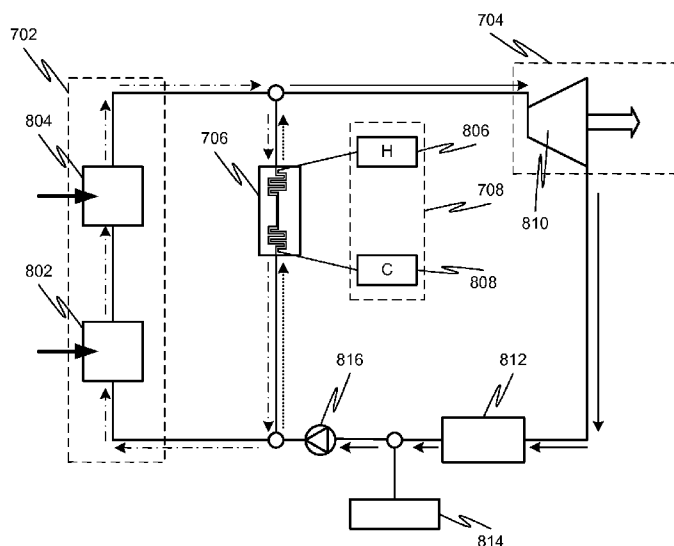
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(54) **Title:** SOLAR ENERGY THERMAL STORAGE SYSTEMS, DEVICES, AND METHODS

**FIG. 8**

(57) **Abstract:** Insolation can be used to heat pressurized water to produce supercritical steam for use in generating electricity (e.g., via a steam turbine). During periods of relatively higher insolation, there can be more heat energy (i.e., enthalpy) in the supercritical than what is needed or desired for electricity generation or can be used within the capacity constraints of a provided power block. Alternatively or additionally, it may be desirable to store energy from insolation to supplement or provide electricity generation at a later time. In general, enthalpy in supercritical steam produced by the insolation can be stored in a thermal storage system (i.e., charging the storage system) for subsequent use, for example, during periods of relatively lower insolation or at times when supplemental electricity generation is desired. The use of supercritical steam can result in a higher temperature for the thermal storage system, which can be used to generate superheated steam independent of or in addition to insolation steam generation.

SOLAR ENERGY THERMAL STORAGE SYSTEMS, DEVICES, AND METHODSCROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Application No.

5 61/514,196, filed August 2, 2011, which is incorporated by reference herein in its entirety.

FIELD

The present disclosure relates generally to energy production using solar insolation, and, more particularly, to storage of solar energy using thermal storage reservoirs.

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SUMMARY

Insolation can be used to heat pressurized water to produce supercritical steam for use in generating electricity (e.g., via a steam turbine). During periods of relatively higher insolation, there can be more heat energy (i.e., enthalpy) in the supercritical steam than what is needed or
15 desired for electricity generation or can be used within the capacity constraints of a provided power block. Alternatively or additionally, it may be desirable to store energy from insolation to supplement or independently provide electricity generation at a later time. In general, enthalpy in supercritical steam produced by the insolation can be stored in a thermal storage system (i.e., charging the storage system) for subsequent use, for example, during periods of relatively lower
20 insolation or at times when supplemental electricity generation is desired (e.g., during peak demand periods or when higher energy prices are available). The use of supercritical steam can result in a higher temperature for the thermal storage system, which can be used to generate superheated steam independent of or in addition to insolation steam generation.

In one or more embodiments of a method of generating electricity, during a first
25 operating, supercritical steam can be produced using insolation on a solar receiver. The supercritical steam can have a temperature and pressure greater than the critical point of water. During the first operating period, a first turbine can be driven using a first portion of the supercritical steam to generate electricity. During the first operating period, a second turbine can be driven using exhaust from the first turbine to generate electricity. During the first
30 operating period, a second portion of the supercritical steam can be co-flowed with a thermal storage fluid along respective flowpaths through a heat exchanger such that enthalpy in the supercritical steam second portion is transferred to the flowing thermal storage fluid.

The method of generating electricity can further include, during a second operating period, flowing pressurized feedwater together with the thermal storage fluid along the

respective flowpaths through the heat exchanger such that a first portion of the enthalpy in the thermal storage fluid is transferred to the pressurized feedwater so as to produce superheated steam. During the second operating period, the first turbine can be driven using the superheated steam to generate electricity. During the second operating period, the exhaust from the first
5 turbine can be flowed through a reheat heat exchanger together with the thermal storage fluid such that a second portion of the enthalpy in the thermal storage fluid heats the exhaust. During the second operating period, the second turbine can be driven using the heated exhaust from the reheat heat exchanger to generate electricity.

In one or more embodiments, a system for generating electricity can include a solar
10 collection system, a thermal storage system, electricity generating system, a heat exchanger system, and a control system. The solar collection system can be constructed to produce supercritical steam using insolation. The thermal storage system can have first and second thermal storage reservoirs for holding a thermal storage fluid therein. The electricity generating system can have first and second turbines. The first turbine can be constructed to accept steam
15 at supercritical temperature and pressure. Each turbine can be configured to generate electricity using steam provided thereto, for example, by driving an electricity generator. An outlet of the first turbine can be operatively coupled to an inlet of the second turbine. The heat exchanger system can thermally couple the solar collection system and the thermal storage system to each other such that enthalpy in one of the solar collection system and the thermal storage system can
20 be transferred to the other. The control system can operate the solar collection, thermal storage, electricity generating, and heat exchanger systems.

The control system can be configured to control the systems such that during a first operating mode, a thermal storage fluid flows from the first reservoir to the second reservoir by way of the heat exchanger system such that enthalpy in a portion of the supercritical steam
25 produced by the solar collection system is transferred to the flowing thermal storage fluid while the remainder of the supercritical steam is used by the first turbine to generate electricity. The control system can be further configured to control the systems such that during a second operating mode, the thermal storage fluid flows from the second reservoir to the first reservoir by way of the heat exchanger system such that enthalpy in the thermal storage fluid heats
30 pressurized feedwater to produce superheated steam. The first turbine can use the superheated steam to generate electricity.

In one or more embodiments, a method for generating electricity can include using insolation to generate supercritical steam. The supercritical steam can have a temperature and pressure in excess of the critical point of water. The method can further include storing enthalpy

from a portion of the supercritical steam in a thermal storage fluid while simultaneously driving a first turbine with the remaining supercritical steam to generate electricity. The method can also include, after the storing, using the stored enthalpy to produce superheated steam from pressurized feedwater and driving the first turbine with the superheated steam to generate electricity. Alternatively or additionally, the method can include, after the storing, using the stored enthalpy to produce steam from pressurized feedwater, using insolation to further heat the produced steam, and driving either the first turbine or the second turbine with the further heated steam to generate electricity. Alternatively or additionally, the method can include, after the storing, using stored enthalpy to produce steam while also using insolation to produce steam, combining the steam produced using enthalpy and insolation, and driving the first turbine with the combined steam to generate electricity. Alternatively or additionally, the method can include, after the storing, using stored enthalpy to produce steam while also using insolation to produce steam, driving the first turbine with the steam from insolation, and driving the second turbine with the steam from stored enthalpy and, optionally, the exhaust from the first turbine, to generate electricity. In any of the embodiments of the method, the exhaust from the first turbine can be optionally reheated by insolation, by stored enthalpy, or by enthalpy entrained in steam and/or water.

In one or more embodiments of a method of generating electricity from insolation and/or thermal storage fluid, at a first time, insolation can be used to generate supercritical steam from pressurized liquid water. At the first time, a first portion of the supercritical steam can be subjected to a heat transfer operation whereby enthalpy of the supercritical steam is conductively or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the supercritical steam to a second temperature. At the first time, a second portion of the supercritical steam can be used to drive a steam turbine to generate electricity.

The method of generating electricity from insolation and/or thermal storage fluid can also include, at a second time, transferring enthalpy from the thermal storage fluid at the first temperature to pressurized liquid feedwater to generate superheated steam at a same pressure as the liquid feedwater and to cool the thermal storage fluid. At the second time, the superheated steam can be used to drive the steam turbine to generate electricity.

In one or more embodiments of a method of generating electricity from insolation and/or thermal storage fluid, at a first time, insolation can be used to generate supercritical steam from pressurized liquid water. At the first time, a first portion of the supercritical steam can be subjected to a heat transfer operation whereby enthalpy of the supercritical steam is conductively

or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the supercritical steam to a second temperature. At the first time, a second portion of the supercritical steam can be used to drive a steam turbine to generate electricity.

- 5 The method of generating electricity from insolation and/or thermal storage fluid can also include, at a second time, transferring enthalpy from the thermal storage fluid to pressurized liquid feedwater at a first pressure to produce saturated steam at the first pressure. At the second time, enthalpy can be transferred from the thermal storage fluid to low-pressure steam at a second pressure obtained from the steam turbine so as to further heat the low-pressure steam.
- 10 The second pressure can be less than the first pressure. At the second time, enthalpy can be transferred from the thermal storage fluid to saturated steam at the first pressure to produce superheated steam.

- In one or more embodiments, a system for electricity generating can include a first solar receiver, a thermal energy storage system, and a heat exchanger assembly. Pressurized
- 15 feedwater can be heated in the first solar receiver by insolation to generate supercritical steam. The thermal energy storage system can include hot and cold reservoirs of a sensible heat storage liquid. The heat exchanger assembly can have one or more heat exchangers. The heat exchanger assembly can be constructed to transfer heat between the supercritical steam and the sensible heat storage liquid during charging of the thermal energy storage system and between
- 20 the sensible heat storage liquid and pressurized water and/or steam during discharging of the thermal energy storage system.

- In one or more embodiments of a method of generating electricity from insolation and/or thermal storage fluid, at a first time, insolation can be used to generate supercritical steam from pressurized liquid water. At the first time, a first portion of the supercritical steam can be
- 25 subjected to a heat transfer operation whereby enthalpy of the supercritical steam is conductively or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the supercritical steam to a second temperature. At the first time, a second portion of the supercritical steam can be used to drive a first steam turbine to generate electricity.

- 30 The method of generating electricity from insolation and/or thermal storage fluid can also include, at a second time, transferring enthalpy from the thermal storage fluid to liquid feedwater at a first pressure to generate superheated steam at the first pressure. At the second time, enthalpy can be transferred from the thermal storage fluid to liquid feedwater at a second pressure to generate superheated steam at the second pressure. The second pressure can be less

than the first pressure. At the second time, the superheated steam at the first pressure can be used to drive the first steam turbine to generate electricity. At the second time, the superheated steam at the second pressure can be used to drive a second steam turbine to generate electricity.

In one or more embodiments, a system for generating electricity can include a first solar receiver, a thermal energy storage system, and a heat exchanger assembly. Pressurized feedwater can be heated in the first solar receiver using insolation to generate supercritical steam. The thermal energy storage system can include hot and cold reservoirs for a sensible heat storage liquid. The heat exchanger assembly can include at least four heat exchangers. The heat exchanger assembly can be constructed to transfer heat between the supercritical steam and the sensible heat storage liquid during charging of the thermal energy storage system and between the sensible heat storage liquid and pressurized water during discharging of the thermal energy storage system. At least two of the heat exchangers can be constructed to operate at a different pressure than the other heat exchangers.

Objects and advantages of embodiments of the disclosed subject matter will become apparent from the following description when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments will hereinafter be described with reference to the accompanying drawings, which have not necessarily been drawn to scale. Where applicable, some features have not been illustrated to assist in the illustration and description of underlying features. Throughout the figures, like reference numerals denote like elements. However, in FIGS. 9A-9F and 12A-12F, not all of the reference numerals have been shown in each figure for clarity and readability purposes.

FIG. 1 shows a solar power tower system, according to one or more embodiments of the disclosed subject matter.

FIG. 2 shows a solar power tower system with secondary reflector, according to one or more embodiments of the disclosed subject matter.

FIG. 3 shows a solar power tower system including multiple towers, according to one or more embodiments of the disclosed subject matter.

FIG. 4 shows a solar power tower system including multiple receivers in a single tower, according to one or more embodiments of the disclosed subject matter.

FIG. 5 is a schematic diagram of a heliostat control system, according to one or more embodiments of the disclosed subject matter.

FIG. 6A is a simplified diagram showing a first arrangement for and connections between the storage reservoirs of a thermal storage system, according to one or more embodiments of the disclosed subject matter.

FIG. 6B is a simplified diagram showing alternative connections between the storage
5 reservoirs of a thermal storage system, according to one or more embodiments of the disclosed subject matter.

FIG. 7A is a simplified diagram showing the interaction between a solar collection system, a thermal storage system, and an electricity generation system during a charging mode, according to one or more embodiments of the disclosed subject matter.

10 FIGS. 7B-7C are simplified diagrams showing the interaction between a solar collection system, a thermal storage system, and an electricity generation system during a first and second discharging modes, respectively, according to one or more embodiments of the disclosed subject matter.

FIG.8 shows a configuration for various components of a solar collection system
15 including a superheating receiver, a thermal storage system, and an electricity generation system, according to one or more embodiments of the disclosed subject matter.

FIGS. 9A-9B illustrate a charging configuration for a solar collection system, a thermal storage system, a multi-section heat exchanger with reheat heat exchanger, and an electricity generation system, according to one or more embodiments of the disclosed subject matter.

20 FIGS. 9C-9F illustrate various discharging configurations for the system of FIGS. 9A-9B, according to one or more embodiments of the disclosed subject matter.

FIG. 10 is a graph illustrating heat exchanger performance during the charging configuration of FIG. 9B and during the discharging configuration of FIG. 9C, according to one or more embodiments of the disclosed subject matter.

25 FIG. 11 is a graph illustrating heat exchanger performance during the charging configuration of FIG. 12B and during the discharging configuration of FIG. 12C, according to one or more embodiments of the disclosed subject matter.

FIGS. 12A-12B illustrate a charging configuration for a solar collection system, a thermal storage system, four heat exchangers, and an electricity generation system, according to
30 one or more embodiments of the disclosed subject matter

FIGS. 12C-12F illustrate various discharging configurations for the system of FIGS. 12A-12B, according to one or more embodiments of the disclosed subject matter.

DETAILED DESCRIPTION

Insolation can be used by a solar tower system to generate supercritical steam and/or for heating molten salt. In FIG. 1, a solar tower system can include a solar tower 50 that receives reflected focused sunlight 10 from a solar field 60 of heliostats (individual heliostats 70 are illustrated in the left-hand portion of FIG. 1 only). For example, the solar tower 50 can have a height of at least 25 meters, 50 meters, 75 meters, or higher. The heliostats 70 can be aimed at solar energy receiver system 20, for example, a solar energy receiving surface of one or more receivers of system 20. Heliostats 70 can adjust their orientation to track the sun as it moves across the sky, thereby continuing to reflect sunlight onto one or more aiming points associated with the receiver system 20. A solar energy receiver system 20, which can include one or more individual receivers, can be mounted in or on solar tower 50. The solar receivers can be constructed to heat water and/or steam and/or supercritical steam and/or any other type of solar fluid using insolation received from the heliostats. Alternatively or additionally, the target or receiver 20 can include, but is not limited to, a photovoltaic assembly, a steam-generating assembly (or another assembly for heating a solid or fluid), a biological growth assembly for growing biological matter (e.g., for producing a biofuel), or any other target configured to convert focused insolation into useful energy and/or work.

The solar energy receiver system 20 can be arranged at or near the top of tower 50, as shown in FIG. 1. In another embodiment, a secondary reflector 40 can be arranged at or near the top of a tower 50, as shown in FIG. 2. The secondary reflector 40 can thus receive the insolation from the field of heliostats 60 and redirect the insolation (e.g., through reflection) toward a solar energy receiver system 20. The solar energy receiver system 20 can be arranged within the field of heliostats 60, outside of the field of heliostats 60, at or near ground level, at or near the top of another tower 50, above or below reflector 40, or elsewhere.

More than one solar tower 50 can be provided, each with a respective solar energy receiving system thereon, for example, a solar power steam system. The different solar energy receiving systems can have different functionalities. For example, one of the solar energy receiving systems can heat water using the reflected solar radiation to generate steam while another of the solar energy receiving systems can serve to superheat steam using the reflected solar radiation. The multiple solar towers 50 can share a common heliostat field 60 or have respective separate heliostat fields. Some of the heliostats can be constructed and arranged so as to alternatively direct insolation at solar energy receiving systems in different towers. In addition, the heliostats can be configured to direct insolation away from any of the towers, for example, during a dumping condition. As shown in FIG. 3, two solar towers can be provided,

each with a respective solar energy receiving system. A first tower 50A has a first solar energy receiving system 20A while a second tower 50B has a second solar energy receiving system 20B. The solar towers 50A, 50B are arranged so as to receive reflected solar radiation from a common field of heliostats 60. At any given time, a heliostat within the field of heliostats 60 can be directed to a solar receiver of any one of the solar towers 50A, 50B. Although only two solar towers with respective solar energy receiving systems are shown in FIG. 3, any number of solar towers and solar energy receiving systems can be employed.

More than one solar receiver can be provided on a solar tower. The multiple solar receivers in combination can form a part of the solar energy receiving system 20. The different solar receivers can have different functionalities. For example, one of the solar receivers can heat water using the reflected solar radiation to generate steam while another of the solar receivers can serve to superheat steam using the reflected solar radiation. The multiple solar receivers can be arranged at different heights on the same tower or at different locations (e.g., different faces, such as a north face, a west face, etc.) on the same tower. Some of the heliostats in field 60 can be constructed and arranged so as to alternatively direct insolation at the different solar receivers. As shown in FIG. 4, two solar receivers can be provided on a single tower 50. The solar energy receiving system 20 thus includes a first solar receiver 21 and a second solar receiver 22. At any given time, a heliostat 70 can be aimed at one or both of the solar receivers, or at none of the receivers. In some use scenarios, the aim of a heliostat 70 can be adjusted so as to move the reflected beam projected at the tower 50 from one of the solar receivers (e.g., 21) to the other of the solar receivers (e.g., 22). Although only two solar receivers and a single tower are shown in FIG. 4, any number of solar towers and solar receivers can be employed.

Heliostats 70 in a field 60 can be controlled through a central heliostat field control system 91, for example, as shown in FIG. 5. For example, a central heliostat field control system 91 can communicate hierarchically through a data communications network with controllers of individual heliostats. FIG. 5 illustrates a hierarchical control system 91 that includes three levels of control hierarchy, although in other implementations there can be more or fewer levels of hierarchy, and in still other implementations the entire data communications network can be without hierarchy, for example, in a distributed processing arrangement using a peer-to-peer communications protocol.

At a lowest level of control hierarchy (i.e., the level provided by heliostat controller) in the illustration there are provided programmable heliostat control systems (HCS) 65, which control the two-axis (azimuth and elevation) movements of heliostats (not shown), for example, as they track the movement of the sun. At a higher level of control hierarchy, heliostat array

control systems (HACS) 92, 93 are provided, each of which controls the operation of heliostats 70 (not shown) in heliostat fields 96, 97, by communicating with programmable heliostat control systems 65 associated with those heliostats 70 through a multipoint data network 94 employing a network operating system such as CAN, Devicenet, Ethernet, or the like. At a still higher level of control hierarchy a master control system (MCS) 95 is provided which indirectly controls the operation of heliostats in heliostat fields 96, 97 by communicating with heliostat array control systems 92, 93 through network 94. Master control system 95 further controls the operation of a solar receiver (not shown) by communication through network 94 to a receiver control system (RCS) 99.

In FIG. 5, the portion of network 94 provided in heliostat field 96 can be based on copper wire or fiber optic connections, and each of the programmable heliostat control systems 65 provided in heliostat field 96 can be equipped with a wired communications adapter, as are master control system 95, heliostat array control system 92 and wired network control bus router 100, which is optionally deployed in network 94 to handle communications traffic to and among the programmable heliostat control systems 65 in heliostat field 96 more efficiently. In addition, the programmable heliostat control systems 65 provided in heliostat field 97 communicate with heliostat array control system 93 through network 94 by means of wireless communications. To this end, each of the programmable heliostat control systems 65 in heliostat field 97 is equipped with a wireless communications adapter 102, as is wireless network router 101, which is optionally deployed in network 94 to handle network traffic to and among the programmable heliostat control systems 65 in heliostat field 97 more efficiently. In addition, master control system 95 is optionally equipped with a wireless communications adapter (not shown).

Insolation can vary both predictably (e.g., diurnal variation) and unpredictably (e.g., due to cloud cover, dust, solar eclipses, or other reasons). During these variations, insolation can be reduced to a level insufficient for heating a solar fluid, for example, producing supercritical steam for use in generating electricity. To compensate for these periods of reduced insolation, or for any other reason, thermal energy produced by the insolation can be stored in a fluid-based thermal storage system for later use when needed. The thermal storage system can store energy when insolation is generally available (i.e., charging the thermal storage system) and later release the energy to heat pressurized water or steam in addition to or in place of insolation. For example, it can be possible at night to replace the radiative heating by insolation to produce superheated steam in the solar collection system with conductive and/or convective heat transfer of thermal energy (i.e., enthalpy) from a thermal storage system to pressurized water and/or steam.

According to one or more embodiments, the receiver may include a boiler wherein preheating and supercritical steam generation may take place. The steam generated in the receiver at supercritical conditions (i.e., at temperatures and pressures in excess of the critical point for water) of more than 220 bar is superheated to a temperature above 600° C, and steam
5 transported from an outlet of a steam turbine with at least a single reheat cycle is optionally reheated therein to a like temperature. For example, the superheated steam is at supercritical conditions of more than 300 bar and is superheated to a temperature of about 620° C. In one or more embodiments of the disclosed subject matter, the receiver may also comprise a superheater section.

10 In a non-limiting example, during daylight hours (i) supercritical steam is generated by subjecting pressurized liquid water to insolation; (ii) a first portion of the steam is used to drive a turbine; and (iii) a second portion of the steam is used to heat a thermal storage fluid of the solar energy storage system via conduction and/or convection. This second portion of steam is used to “charge” the thermal storage system. In a second non-limiting example, during daylight hours,
15 (i) supercritical steam is generated by subjecting pressurized liquid water to insolation; (ii) substantially all of the steam is used to heat a thermal storage fluid of the solar energy storage system via conduction and/or convection. When solar energy is not available, when solar energy is available at less than a rated capacity of the solar power plant, or when it is desirable to produce a greater amount of electricity (e.g., during periods of higher tariffs) enthalpy of the
20 solar energy storage system is used to generate superheated steam via heat conduction and/or convection between the hotter thermal storage fluid and the cooler pressurized liquid water.

According to one or more embodiments of the disclosed subject matter, the enthalpy can be derived from heated molten salt or molten metal. The discharge of the thermal storage system occurs with the transfer of enthalpy from the thermal storage system to the pressurized water.

25 This steam generated from enthalpy of the energy storage system may be used to drive the same turbine that was driven during the daylight hours. Alternatively, any other turbine may be used to generate the electricity. In some embodiments, the turbine, driven by enthalpy of the thermal storage system, operates at a lower pressure than when operating by steam generated by insolation.

30 In one or more embodiments, the thermal storage system includes at least two separate thermal storage reservoirs, which can be substantially insulated to minimize heat loss therefrom. A thermal storage medium can be distributed among or in one of the two storage reservoirs. For example, the thermal storage medium can be a molten salt and/or molten metal and/or other high temperature (i.e., > 250 °C) substantially liquid medium. The thermal storage medium can be

heated by convective or conductive heat transfer from the solar fluid in a heat exchanger. This net transfer of enthalpy to the thermal storage medium in the thermal storage system is referred to herein as charging the thermal storage system. At a later time when insolation decreases, the direction of heat exchange can be reversed to transfer enthalpy from the thermal storage medium to the solar fluid via the same or a different heat exchanger. This net transfer of enthalpy from the thermal storage medium of the thermal storage system is referred to herein as discharging the thermal storage system.

As used herein, the term “charging” a thermal storage system relates to an operation in which heat is transferred from an external source, such as supercritical steam to the thermal storage liquid in order to increase the overall thermal potential of the thermal storage system. In one or more embodiments, “charging” of the thermal storage system can be carried out in parallel with the transferring of thermal storage liquid from a relatively cold storage reservoir to a relatively hot storage reservoir. In some embodiments, the temperature of the cold tank has a temperature of about the melting point of the molten metal and/or molten salt. In some embodiments, the melting point of the molten metal and/or molten salt is 220° C. In some embodiments, the temperature of the cold tank is at least 50° above the melting point of the thermal storage fluid. In one or more non-limiting embodiments of the disclosed subject matter, the thermal storage system is charged when enthalpy is transferred from supercritical steam in order to harvest the enthalpy of the steam and thereby cooling the steam to become sub-cooled liquid, a mixture of steam and water, or saturated steam.

As used herein, the term “discharging” of a thermal storage system refers to the opposite of “charging.” In this operation, heat is transferred from the thermal storage liquid to an external medium in order to decrease the overall thermal potential of the thermal storage system. In some embodiments, the external medium may include pressurized water, pressurized subcritical steam or supercritical steam.

Each thermal storage reservoir can be, for example, a fluid tank or a below-grade pool. Referring to FIG. 6A, a thermal storage system 600A with fluid tanks as the thermal storage reservoir is shown. A first fluid tank 602 can be considered a relatively cold reservoir, in that the temperature during the charging and/or discharging modes is maintained at substantially a temperature of T_C , which is the lowest temperature in the thermal storage system. A second fluid tank 606 can be considered a relatively hot reservoir, in that the temperature during the charging and/or discharging modes is maintained at substantially a temperature of T_H , which is the highest temperature in the thermal storage system.

During the charging phase (flow directions illustrated by dash-dot lines in the figure), thermal storage medium can be transferred from the colder reservoirs of the thermal storage system to the hotter reservoirs of the thermal storage system, as designated by the block arrow in FIG. 6A. During the discharging phase (flow directions illustrated by dotted lines in the figure), the flow of thermal storage medium can be reversed so as to flow from the hotter reservoirs to the colder reservoirs of the thermal storage system, as designated by the block arrow in FIG. 6A. Thus, storage medium in the first reservoir 602 can be transferred via fluid conduit or pipe 608 to the second reservoir 606 in the charging phase and reversed in the discharging phase.

During the charging or discharging modes, enthalpy can be exchanged between the solar fluid and the thermal storage medium as the thermal storage medium passes between the reservoirs. The fluid conduits or pipes can be in thermal communication with the solar fluid by way of a heat exchanger to allow the transfer of enthalpy as the thermal storage fluid flows between reservoirs (i.e., while the thermal storage medium is *en route* to a destination reservoir). For example, conduit 608 connecting the first reservoir 602 to the second reservoir 606 can pass through a heat exchanger 604 such that the thermal storage medium can exchange enthalpy 614 and 616 with the solar fluid. The direction of enthalpy flow depends on the mode of operation, with enthalpy flowing from the solar fluid to the thermal storage medium during the charging phase and from the thermal storage medium to the solar fluid during the discharging phase. Portions of the fluid conduit 608 can be insulated to minimize or at least reduce heat loss therefrom.

Enthalpy 614 can correspond to the decrease in temperature of the solar fluid from an initial superheated temperature to its boiling point temperature while enthalpy 616 can correspond to the release of latent heat as the solar fluid changes phase at the boiling point temperature. In some embodiments of the disclosed subject matter, the temperature of the cold reservoir can be between 270° and 300° C, and the temperature of the hot reservoir can be approximately 510° C. For example, the temperature of the cold reservoir can be approximately 290° C. In one or more non-limiting embodiments, a temperature gap between the cold and the hot reservoirs can be significant, for example, at least 50°C, 100°C, 150°C, 200°C, 250°C or more.

The particular arrangement and configuration of fluid conduit 608 in FIG. 6A is for illustration purposes only. Variations of the arrangement, number, and configuration of the fluid conduit are also possible according to one or more contemplated embodiments. Such a variation is shown in FIG. 6B, where fluid conduit 628 is provided between the different reservoirs of the thermal storage system 600B. As with the configuration of FIG. 6A, one or more heat

exchangers can be placed in thermal communication with the fluid conduit to enable transfer of enthalpy 614, 616. In addition, multiple fluid conduits can be provided in parallel, such that fluid flowing between the reservoirs can be distributed across the multiple conduits.

Alternatively or additionally, multiple fluid conduits can be provided in parallel, but with fluid
5 flow in one conduit being opposite to that in the other conduit. For example, a return conduit can be provided between the first reservoir and the second reservoir in addition to a forward conduit such that at least some fluid can be returned to the first reservoir. The direction of the net flow between the reservoirs (i.e., the flow in the forward conduit(s) minus the flow in the reverse conduit(s)) can depend on the particular mode of operation. For example, the net flow in
10 the charging phase can be from the colder reservoir to the hotter reservoir and reversed in the discharging phase.

One or more pumps (not shown) can be included for moving the thermal storage medium between reservoirs. Additional flow control components can also be provided, including, but not limited to, valves, switches, and flow rate sensors. Moreover, a controller (for example, see
15 FIGS. 7A-7C) can be provided. The controller can control the thermal storage fluid medium within the thermal storage system. The controller can include any combination of mechanical or electrical components, including analog and/or digital components and/or computer software. In particular, the controller can control the storage medium flow in tandem with the solar fluid to maintain a desired temperature profile within the thermal storage system for optimal (or at least
20 improved) heat transfer efficiency. For example, the first and second reservoirs can be maintained at a temperature, T_C , above the melting point of the thermal storage medium such that the thermal storage medium remains in a substantially fluid phase so as to allow pumping of the thermal storage medium.

Referring to FIGS. 7A-7C, simplified diagrams of the interaction of a solar collection
25 system, a thermal storage system, and an electricity generation system during various charging and discharging phases are shown. In particular, FIG. 7A shows the system setup 700 and the general flow of heat and fluids during a charging phase. FIG. 7B shows the system setup and the general flow of heat and fluids during discharging phase where insolation is still available. The thermal storage system thus provides a boost to the supercritical steam generation by
30 providing steam to the solar concentration system. FIG. 7C shows the system setup and the general flow of heat and fluids during a discharging phase where insolation may be too low or unavailable. The thermal storage thus provides steam directly to the electricity generation system independently or together with the solar collection system.

In FIGS. 7A-7C, a thick arrow represents energy transfer, either in the form of insolation or enthalpy; a dotted arrow represents the flow of water; and a dash-dot arrow represents the flow of steam. Although FIGS. 7A-7C are discussed with respect to water/steam as the solar fluid, it should be understood that other solar fluids can also be used according to one or more contemplated embodiments.

Referring now to FIG. 7A, a charging phase of the thermal storage system 708 is shown. A solar collection system 702 can receive insolation and use the insolation to produce supercritical steam from pressurized feedwater 712. The supercritical steam can have a temperature and pressure in excess of the critical point for water (e.g., approximately 374°C and 221 bar). The resulting supercritical steam can be output from the solar collection system 702 and split into at least two portions: a first portion designated for thermal storage and a second portion designated for electricity generation. The relative proportions of the first and second portions can be based on a variety of factors, including, but not limited to, the amount of enthalpy in the generated steam, current electricity demand, current electricity pricing, and predicted insolation conditions. A control system 710 can be provided for regulating the operation of the solar collection system 702, the thermal storage system 708, the electricity generation system 704, the one or more heat exchangers 706, and/or other system or flow control components (not shown).

The first portion of the supercritical steam can be directed to an electricity generation system 704, which uses the first portion of the steam to produce electricity and/or other useful work. For example, the electricity generation system 704 can include a plurality of turbines. Eventually, the steam can be condensed to produce water, which can be directed back to the solar collection system 702 for subsequent use in producing steam. Meanwhile, the second portion of the supercritical steam can be directed to heat exchanger 706. The heat exchanger 706 is in thermal communication with a thermal storage system 708. Steam entering the heat exchanger 706 releases enthalpy (via conduction and/or convection) to the thermal storage system 708. During this process, thermal storage fluid flows internally from a cold tank of the thermal storage system to a hot tank thereof, for example, as shown in FIG. 6A. The insolation received by the working fluid in solar thermal system 702 may be provided by re-directed sunlight from a plurality of heliostats or from any other solar reflection apparatus, such as a trough-based system, or in any other manner, according to one or more contemplated embodiments.

When insolation is present but a boost of steam production is desired, (for example, to take advantage of higher electricity rates), the setup of FIG. 7B for discharging the thermal

storage system 708 can be used. In contrast to FIG. 7A, the direction of feedwater in FIG. 7B is reversed such that water is input to the one or more heat exchangers 706. The direction of enthalpy flow in FIG. 7B is also reversed, such that heat is transferred (via conduction and/or convection) from the thermal storage system 708 to the heat exchanger 706 to heat the
5 pressurized water flowing therethrough.

During the discharging phase shown in FIG. 7B, the working fluid for the solar collection system 702 is heated by enthalpy conductively and/or convectively transferred from the thermal storage system 708 (i.e., from storage liquid within the storage system) to induce a phase change in the working fluid (e.g., to evaporate pressurized water) and/or to transfer
10 sensible heat to the working fluid after the phase change (i.e., to superheat sub-critically). The steam is directed to the solar collection system 702 where the steam is further heated by insolation before being directed to the electricity generation system 704 to drive a turbine therein to generate electricity. The turbine may operate at a lower pressure and/or temperature during discharging phases than it did during the charging.

When insolation is sufficiently low or non-existent, (for example, only capable of producing low-pressure steam), the setup of FIG. 7C for discharging the thermal storage system 708 can be used. In contrast to FIG. 7B, the steam produced by the transfer of enthalpy from the thermal storage system 708 to pressurized feedwater in heat exchanger 706 can be provided
15 directly to the electricity generating system 704. Any steam produced by the solar collection system 702 using insolation may be combined with the steam from the heat exchanger 706. The steam from the heat exchanger 706, and potentially from the solar collection system 702, can drive a turbine in the electricity generating system 704 to produce electricity. Thus, the thermal storage system may allow buffering of insolation energy for use during times of bad weather conditions (e.g., cloud cover), curtailment of solar energy on demand, and boosting of solar
20 energy production during high tariff periods to maximize or at least increase revenue production. In addition, embodiments of the disclosed subject matter may allow for energy shifting from periods of low tariffs to periods of high tariffs.

The systems can be controlled responsively to one or more of the disclosed conditions, or any other condition, to switch between a charging mode of the thermal storage system and the
30 discharging modes of the thermal storage system. Such control may be performed by one or more control systems. For example, the control system may provide a charging mode during a high insolation period of the day, switch to a discharging only mode during a period of cloud cover, switch back to a charging mode when insolation has recovered, switch to a boost

discharging mode during an afternoon period when tariffs are particular high, and switch to another boost discharging mode during an evening period when insolation levels are declining.

FIG. 8 shows a configuration of a solar collection system including a solar supercritical steam generator 802 and an optional superheater 804 for further superheating the steam. In contrast to a solar boiler where the phase change driven by insolation is a sub-critical evaporation of pressurized water, a supercritical fluid is generated in supercritical steam generator 802 from pressurized water using insolation (or using any other enthalpy source). Superheater 804 thus produces superheated/further heated supercritical steam rather than superheated/further heated subcritical steam.

A first portion of the pressurized superheated, supercritical steam can be sent to turbine 810 (e.g., to generate electricity) while a second portion of the pressurized superheated, supercritical steam can be sent to a heat exchanger assembly 706 of one or more heat exchangers. In heat exchanger 706, enthalpy is transferred from the superheated, supercritical steam to a thermal storage fluid flowing between a hot reservoir 806 and a cold reservoir 808 in thermal storage system 708. The transfer of enthalpy condenses the steam so as to exit the heat exchanger 706 as pressurized water. The pressurized water can be combined with pressurized feedwater for further re-use by solar collection system 702. For example, feedwater from source 814 can be pressurized by pump 816 and combined with the condensed water from the heat exchanger 706. Alternatively or additionally, driving the turbine 810 with the superheated, supercritical steam can cause reduce the temperature of the steam or cause it to condense. Condenser 812 may condition the exhaust from the turbine 810 for reintroduction with the pressurized feedwater to the solar collection system 704 by way of pump 816.

FIGS. 9A-9F illustrate an embodiment using a multi-stage heat exchanger and a reheat heat exchanger in different operating modes. Note that in FIGS. 9A-9F, not all reference numerals have been shown in each figure for clarity and readability purposes; however, the reference numerals for elements unlabeled in a particular figure should be readily apparent from examination of the other figures. FIG. 10 is a graph of heat transfer duty versus temperature for various fluids during charging and discharging modes of the system of FIG. 9A. In FIG. 10, curve 1002 represents the thermal storage fluid during charging and curve 1006 represents the thermal storage fluid during discharging; curve 1004 represents the water/steam in heat exchanger 914 during charging and curve 1008 represents the water/steam in heat exchanger 914 during discharging; curve 1010 represents the water/ steam in reheat heat exchanger 916 during discharging.

Referring to FIG. 9A, a solar collection system 702 can include a solar receiver 904 which receives insolation thereon for heating pressurized water passing therethrough to produce supercritical steam. Electricity generating system can include a first turbine 910 and a second turbine 912. The first turbine 910 can be constructed to operate at a higher pressure than the second turbine 912, and thus are referred to herein as high pressure turbine 910 and low pressure turbine 912. Although the turbines 910, 912 are shown and described as separate turbines, in practice they may be different portions of the same turbine. For example, high pressure turbine 910 can represent a high pressure input portion of a turbine while low pressure turbine 912 can represent an intermediate input portion of the turbine.

Thermal storage system 708 can include a cold reservoir 908 and a hot reservoir 906 for holding the thermal storage fluid therein. The reservoirs 906, 908 can be fluidically connected to heat exchanger 706 such that the thermal storage fluid passes therethrough for enthalpy exchange with water and/or steam also flowing through the heat exchanger 706. Heat exchanger 706 can include a multi-stage heat exchanger 914 and a reheat heat exchanger 916. In particular, the multi-stage heat exchanger 914 can include a first stage 914a and a second stage 914b. The first stage 914a may operate at a higher temperature than the second stage 914b. The first stage 914a can thus be connected to the hot reservoir 906 while the second stage 914b is connected to the cold reservoir 908. Reheat heat exchanger 916 is operatively connected in the thermal fluid flowpath between the first and second stages 914a, 914b and thus operates at an intermediate temperature.

Referring to FIG. 9B, a configuration for charging of the thermal storage system 708 using supercritical steam produced by solar receiver 904 is shown. For example, the solar receiver uses the insolation to produce steam at a temperature of 620° C and a pressure of 300 bar. A first portion of this supercritical fluid is sent to inlet 946 of high pressure steam turbine 910 to generate useful work (i.e., to drive a generator to produce electricity). The fluid depressurized within the high pressure turbine 910 is exhausted at outlet 948. The exhaust may be directed back to an inlet 942 of the solar receiver 904 to be re-heated using insolation. The additionally heated exhaust exits the solar receiver 904 at 944 and is directed to inlet 950 of low pressure turbine 912.

A second portion of the supercritical steam from the solar receiver 904 enters heat exchanger 914 at inlet 934 to heat the thermal storage liquid of the thermal storage system. The thermal storage liquid can have an initial temperature above the melting point of the storage fluid (i.e., in liquid phase) but below the critical point temperature of water. As enthalpy is transferred to the thermal storage fluid as it flows from the cold reservoir 908 to the hot reservoir

906 by way of sequential flowpaths through the second heat exchanger section 914b, the reheat heat exchanger 916, and the first heat exchanger section 914a, the thermal storage fluid is heated to a significantly higher temperature.

The first section 914a of the heat exchanger 914 can operate at a higher temperature than the second section 914b of the heat exchanger. The thermal storage liquid entering the second section 914b at inlet 928 can gain heat via heat conduction and/or convection as it passes through the heat exchanger and subsequently flows to the hot storage reservoir 906. While inlet or outlet has been adopted for convenience of terminology herein, it is to be appreciated that this does not limit the operation of the specific feature. For example, inlet 928 serves as input to the thermal storage fluid flowpath through heat exchanger section 914b during charging, but serves an output from the same flowpath during discharging operations.

The thermal storage liquid exiting the second section 914b at outlet 926 is sent to inlet 924 of reheat heat exchanger 916. No steam may be directed through the reheat heat exchanger 916 (i.e., from inlet 952 to outlet 930) during the charging phase, in which case the reheat heat exchanger may simply allow flowthrough of the thermal storage fluid to the first section 914a without substantially heating occurring therein. Alternatively, supercritical steam can also be directed through the reheat heat exchanger 916 simultaneously with the direction through the heat exchanger 914 to allow further heating of the thermal storage liquid en route to the first heat exchanger section 914a.

The thermal storage liquid exiting the reheat heat exchanger 916 at outlet 922 is sent to inlet 920 of the first heat exchanger section 914a, where it is further heated to a final temperature by the supercritical steam flowing through the heat exchanger 914. The heated thermal storage liquid exits the first heat exchanger section 914a at outlet 918 and is stored in hot reservoir 906 until needed for discharging. For example, the thermal storage hot temperature reservoir may have a temperature of 510°C. Transfer of enthalpy to the thermal storage system (i.e., charging rate) may be on the order of hundreds of MW_{th}, for example, 159 MW_{th} and may take on the order of several hours, for example, 8.2 hours, to fully charge the storage system. The thermal storage system can have several thousand tons of thermal storage fluid contained therein, for example, over 14,000 tons occupying a volume of over 7600 cubic meters.

Meanwhile, the supercritical steam flowing from inlet 934 to outlet 936 of the heat exchanger 914 can be condensed into pressurized sub-cooled water. Although the formerly supercritical steam is substantially de-superheated by passing through heat exchanger 914, the resulting water remains substantially pressurized. For example, the pressure drop between the

input supercritical steam and the water output from the heat exchanger can be no more than 50%, 30%, 20%, 10%, or less. Thus, the water may be directed back to inlet 938 of the solar receiver 904 together with pressurized feedwater 940 for producing additional supercritical steam from insolation. Alternatively or additionally, the sub-cooled water may be utilized to
5 heat the pressurized feedwater 940 prior to introduction to the solar receiver 904, for example, by directing to a second heat exchanger (not shown).

Steam provided to an input of the heat exchanger for transferring heat to the thermal storage fluid can have a temperature of 620°C at a pressure of 300 bar and a flow rate of 77 kg/s (see D in FIG. 9B). Steam produced for the low pressure turbine by the solar collection system
10 may have a temperature of 620°C at a pressure of 300 bar and a flow rate of 206 kg/s (see C in FIG. 9B). Feedwater provided to the solar collection system can have a temperature of 268°C at a pressure of 350 bar and a flow rate of 206 kg/s (see B in FIG. 9B). The output of the heat exchanger after charging may be water having a temperature of 320°C at a pressure of 286 bar and a flow rate of 77 kg/s (see A in FIG. 9B). The thermal storage fluid may pass through the
15 heat exchanger at a flow rate of 477 kg/s during charging.

During periods of no or low insolation (e.g., at night or during cloudy periods), enthalpy stored in the thermal storage fluid can be used to run turbines 910 and 912. FIG. 9C illustrates configuration of the system in such a discharging mode, where the thermal storage system can generate steam at sub-critical conditions. Pressurized feedwater 940 is provided to heat
20 exchanger 914 in a direction of flow opposite to that of the charging shown in FIG. 9B. The pressurized feedwater is heated by heat conduction and/or convection as it passes through the heat exchanger to produce superheated steam, which is then provided to the high pressure turbine 910 to generate useful work. The fluid depressurized within the high pressure turbine 910 can be provided to inlet 930 of reheat heat exchanger 916. Thermal storage fluid flows
25 through the reheat heat exchanger 916 in a direction of flow opposite to that in the charging shown in FIG. 9B. The depressurized fluid is heated by heat conduction and/or convection as it passes through the reheat heat exchanger 916 to produce steam, which is then provided to the low pressure turbine 912 to generate useful work.

An auxiliary boiler 954 (see FIG. 9F), e.g., a gas-fired boiler, can be used to boost
30 system operation, for example, during periods when the thermal storage system is approaching depletion or when additional power output is needed. The auxiliary boiler 954 can provide supplemental steam to the input 950 of the low pressure turbine 912.

During discharge, the thermal storage fluid flows from hot reservoir 906 to inlet 918 of heat exchanger 914. Heat is transferred from the thermal storage fluid to the feedwater as it

passes through the heat exchanger 914. The thermal storage fluid exits the first heat exchanger section 914a and is directed to reheat heat exchanger 916, where it transfers additional heat therein to the steam exiting from high pressure turbine 910. As noted above, the steam exiting reheat heat exchanger 916 at 952 flows to low pressure turbine 912. The thermal storage fluid from the reheat heat exchanger 916 re-enters the heat exchanger 914 at inlet 926 of the second section 914b. The arrangement of the first and second heat exchanger sections can be such that the thermal storage fluid entering the second heat exchanger section 914b (i.e., at inlet 926) is in thermal contact with feedwater entering the heat exchanger before the feedwater comes in thermal contact with the thermal storage fluid in the first heat exchanger section 914a (i.e., entering at inlet 918). The thermal storage fluid exits the second heat exchanger section 914b at 928 and is stored in cold reservoir 908 for later use.

In order to prevent freezing of the thermal storage fluid, the temperature of the feedwater introduced to the heat exchanger 914 can be greater than 220° C. In some embodiments the temperature of the feedwater is at least 240° C, 260° C, or greater. For example, the thermal storage system may have a maximum discharge rate that produces on the order of hundreds of MW_e, for example, between 140 and 150 MW_e of electrical power. This discharge rate can generate steam at subcritical conditions, for example, about 435 °C and 165 bar. The thermal storage system discharge rate can provide, for example, 328 MW_{th}. The thermal storage system may be capable of providing several hours of discharge, for example, 4 hours.

Steam produced by the heat exchanger for use by the high pressure turbine can have a temperature of 435 °C at a pressure of 165 bar and a flow rate of 130 kg/s (see A in FIG. 9C). Steam reheated for the low pressure turbine by the thermal storage system may have a temperature of 410 °C at a pressure of 48 bar and a flow rate of 130 kg/s (see C in FIG. 9C). Feedwater provided to the heat exchanger can have a temperature of 212 °C at a pressure of 175 bar and a flow rate of 130 kg/s (see B in FIG. 9C). The exhaust of the high pressure turbine may have a temperature of 279 °C at a pressure of 49 bar and a flow rate of 130 kg/s (see D in FIG. 9C). The thermal storage fluid may pass through the heat exchanger at a flow rate of 984 kg/s during discharging.

During periods of relatively high insolation (i.e., when the solar load of the solar collection system is 60% or greater of maximum continuous rating of the system), enthalpy in the thermal storage system can be used to boost supercritical steam production by insolation. In such a configuration, the thermal storage system may operate in series, as shown in FIG. 9D. Pressurized feedwater 940 can be fed into heat exchanger 914 while the thermal storage system discharges (i.e., while thermal storage fluid flows from the hot reservoir 906 to the cold

reservoir 908 by way of the first heat exchanger section 914a, the reheat heat exchanger 916, and the second heat exchanger section 914b) so as to pre heat the feedwater. For example, the temperature of water at an outlet 934 of the heat exchanger 914 can be less than 350° C, 300° C, or less. Alternatively, the heating in the heat exchanger 914 may be sufficient to produce steam at outlet 934.

The output from the heat exchanger 914 can be provided to solar receiver 904, which uses insolation incident thereon to produce supercritical steam, which may be at higher temperature than that obtained in the charging configuration of FIG. 9B. The supercritical steam can be used to drive high pressure turbine 910 to generate useful work. Depressurized exhaust from the high pressure turbine 910 can be provided to inlet 942 of solar receiver 904 for reheating. The reheated exhaust can be used to drive low pressure turbine 912 to generate useful work.

During periods of relatively low insolation (i.e., when the solar load of the solar collection system is between 20% and 60% of maximum continuous rating of the system), enthalpy in the thermal storage system can be used to provide a system boost by concurrent steam production with insolation. In such a configuration, the thermal storage system may operate in parallel, as shown in FIG. 9E.

Pressurized feedwater 940 can be fed into heat exchanger 914 while the thermal storage system discharges (i.e., while thermal storage fluid flows from the hot reservoir 906 to the cold reservoir 908 by way of the first heat exchanger section 914a, the reheat heat exchanger 916, and the second heat exchanger section 914b) so as to produce steam. Such steam may be superheated (e.g., have a temperature of about 435°C) but at a pressure less than the critical point of water (e.g., at a pressure of about 165 bar). Steam produced using insolation in solar receiver 904 can be combined with the steam from the heat exchanger 914. The steam produced by the solar receiver may also be subcritical due to the low or declining insolation levels.

However, use of this mode of operation may only be available once the pressure of the steam from the solar receiver 904 matches the pressure of the steam from heat exchanger 914 (e.g., 165 bar). If the solar collection system is producing steam having a greater pressure than that exiting the heat exchanger, the solar collection system can operate in sliding pressure mode until the two pressures are the same, after which the pressure is maintained at the common pressure. While the solar collection system and the heat exchanger may produce steam at the same pressure, the temperatures of the steam may be at different temperatures. Appropriate mechanisms can be used to combine the different temperature steam flows prior to introduction to the high pressure turbine.

The steam from both the solar receiver 904 and the heat exchanger 914 can be used to drive high pressure turbine 910 to generate useful work. As with other configurations, depressurized exhaust from the high pressure turbine 910 can be provided to inlet 942 of solar receiver 904 for reheating. The reheated exhaust can be used to drive low pressure turbine 912 to generate useful work.

FIGS. 12A-12F illustrate an embodiment using a multiple heat exchanger in different operating modes. Note that in FIGS. 12A-12F, not all reference numerals have been shown in each figure for clarity and readability purposes; however, the reference numerals for elements unlabeled in a particular figure should be readily apparent from examination of the other figures.

FIG. 11 is a graph of heat transfer duty versus temperature for various fluids during charging and discharging modes of the system of FIG. 12A. In FIG. 11, curve 1102 represents the thermal storage fluid during charging and curve 1106 represents the thermal storage fluid during discharging; curve 1104 represents the water/steam in the heat exchanger assembly during charging; curves 1108, 1110, 1112, and 1114 represent the water/steam in the first through fourth heat exchangers, respectively, of the heat exchanger assembly during discharging.

In contrast to FIG. 9A, the embodiment illustrated in FIG. 12A has a heat exchanger system 706 including a plurality of individual heat exchangers 1202-1208 instead of heat exchanger 914 and reheat heat exchanger 916. The flowpaths of the heat exchangers 1202-1208 can be connected in series or in parallel depending on the mode of operation. In addition, the heat exchangers can be constructed to operate at different pressures with respect to the water or steam passing therethrough. For example, a first heat exchanger 1202 and a third heat exchanger 1206 may form a low pressure heat exchanger system 1250 while a second heat exchanger 1204 and a fourth heat exchanger 1208 may form a high pressure heat exchanger system 1255. The heat exchanger system 706 may thus be considered a two-pressure system, the two pressures corresponding to respective operating pressures of the turbines in a discharge operating mode.

Thermal storage system 708 can include a cold reservoir 908 and a hot reservoir 906 for holding the thermal storage fluid therein. The reservoirs 906, 908 can be fluidically connected to the heat exchangers 1202-1208 such that in a charging mode the thermal storage fluid passes through each of the heat exchangers in parallel and in a discharging mode the thermal storage fluid passes serially through the heat exchangers. The first heat exchanger 1202 may operate at a lower temperature than the second heat exchanger 1204, which may in turn operate at a lower temperature than the third heat exchanger 1206. The fourth heat exchanger 1208 may operate at a highest temperature of the heat exchanger system 706.

Referring to FIG. 12B, a configuration for charging of the thermal storage system 708 using supercritical steam produced by solar receiver 904 is shown. For example, the supercritical steam is at a temperature of 620° C and a pressure of 300 bar. A first portion of this supercritical fluid is sent to inlet 946 of high pressure steam turbine 910 to generate useful work (i.e., to generate electricity). The fluid depressurized within the high pressure turbine 910 is exhausted at outlet 948. The exhaust may be directed back to an inlet 942 of the solar receiver 904 to be re-heated using insolation. The additionally heated exhaust exits the solar receiver 904 and is directed to inlet 950 of low pressure turbine 912.

A second portion of the supercritical steam from the solar receiver 904 enters each of the heat exchangers 1202-1208 in parallel via an inlet header 1210 in order to heat the thermal storage liquid of the thermal storage system. The flow rate of supercritical fluid through each of the heat exchangers can be equal, for example. The thermal storage liquid can have an initial temperature above the melting point of the storage fluid (i.e., in liquid phase) but below the critical point temperature of water. As enthalpy is transferred to the thermal storage fluid as it flows from the cold reservoir 908 to the hot reservoir 906 by way of parallel flowpaths through the heat exchangers 1202-1208, the thermal storage fluid is heated by conduction and/or convection to a significantly higher temperature.

The flow rate of thermal storage fluid through each of the heat exchangers can be equal, for example. Accordingly, the temperature of each flow of thermal storage fluid from individual heat exchangers to the hot reservoir is substantially the same. For example, the thermal storage hot temperature reservoir may have a temperature of 510°C. Transfer of enthalpy to the thermal storage system (i.e., charging rate) may be on the order of hundreds of MW_{th}, for example, 180 MW_{th} and may take on the order of several hours, for example, 7.4 hours, to fully charge the storage system. The thermal storage system can have several thousand tons of thermal storage fluid contained therein, for example, over 14,000 tons occupying a volume of over 7800 cubic meters.

Heat exchangers 1202-1208 can be once-through vertical heat exchangers, such as, but not limited to, tube and shell type heat exchangers. Because of the enthalpy transfer to the thermal storage fluid in the heat exchangers 1202-1208, the supercritical steam is condensed into sub-cooled water. Although the formerly supercritical steam is substantially de-superheated by passing through heat exchangers, the resulting water remains substantially pressurized. For example, the pressure drop between the input supercritical steam and the water output from the heat exchanger can be no more than 50%, 30%, 20%, 10%, or less. Thus, the water may be directed back to inlet 938 of the solar receiver 904 together with pressurized feedwater 940 for

producing additional supercritical steam from insolation. Alternatively or additionally, the sub-cooled water may be utilized to heat the pressurized feedwater 940 prior to introduction to the solar receiver 904, for example, by directing to a second heat exchanger (not shown).

Water exiting the heat exchanger assembly after charging the thermal storage system may have a temperature of 320 °C at a pressure of 286 bar and a flow rate of 87 kg/s (see A in FIG. 12B). Steam produced for the low pressure turbine by the solar collection system may have a temperature of 620 °C at a pressure of 300 bar and a flow rate of 206 kg/s (see C in FIG. 12B). Feedwater provided to the solar collection system can have a temperature of 268 °C at a pressure of 350 bar and a flow rate of 206 kg/s (see B in FIG. 12B). The supercritical steam provided to the heat exchanger assembly for charging can be at a temperature of 620 °C at a pressure of 300 bar and a flow rate of 87 kg/s (see D in FIG. 12B). During charging, the thermal storage fluid may flow through the heat exchanger assembly at a flow rate of 477 kg/s.

As noted above and as is shown in FIGS. 12A-12F, the thermal storage system may transfer enthalpy with the solar fluid via a plurality of heat exchangers 1202-1208. This arrangement of heat exchangers can provide steam during the discharging mode at multiple pressures, e.g., superheated sub-critical steam may be produced as high pressure steam and low pressure steam. For example, high pressure steam produced by enthalpy transfer in high pressure heating module 1255 (i.e., second heat exchanger 1204 and fourth heat exchanger 1208) from the thermal storage system can be at a pressure of approximately 210 bar and a temperature of approximately 485° C while low pressure steam produced by enthalpy transfer in low pressure heating module 1250 (i.e., first heat exchanger 1202 and third heat exchanger 1206) from the thermal storage system can be at a pressure of approximately 74 bar and a temperature of approximately 455° C. Other combinations of temperatures and pressures are also possible, depending on the design of the turbine and the optimization of the operating modes of the solar power system, according to one or more contemplated embodiments.

During periods of no or low insolation (e.g., at night or during cloudy periods), enthalpy stored in the thermal storage fluid can be used to run turbines 910 and 912. FIG. 12C illustrates configuration of the system in such a discharging mode, where the thermal storage system can generate steam at sub-critical conditions. To produce superheated steam at two different pressures, feedwater can be provided to the heat exchanger assembly 706 at two separate pressures. For example, high pressure feedwater may be obtained from a feedwater pump, and low pressure feedwater may be obtained from a de-aerator.

The high pressure feedwater 940 can be provided to the second heat exchanger 1204 so as to be heated by the thermal storage fluid via heat conduction and/or convection as it passes

through the second heat exchanger 1204. The steam produced by the second heat exchanger 1204 can be provided to fourth heat exchanger 1208 (i.e., a superheater) for further heating by the thermal storage fluid. The high pressure steam from the fourth heat exchanger 1208 can be used to drive high pressure turbine 910 to generate useful work. In order to prevent freezing of the thermal storage fluid, the temperature of the feedwater provided to the first and second heat exchangers can be greater than 220° C, for example, at least 10% greater, 20% greater, or higher.

The depressurized exhaust from the high pressure turbine 910 can be provided to a third heat exchanger 1206 (i.e., a reheat heat exchanger) for further heating by the thermal storage fluid. Steam output from the third heat exchanger 1206 can be used to drive low pressure turbine 912 to generate useful work. An auxiliary boiler 954 (see FIG. 12F), e.g., a gas-fired boiler, can be used to boost system operation, for example, during periods when the thermal storage system is approaching depletion or when additional power output is needed. The auxiliary boiler 954 can provide supplemental steam to the input 952 of the low pressure turbine 912.

In addition, low pressure feedwater can be provided to a first heat exchanger 1202 so as to be heated by the thermal storage fluid via heat conduction and/or convection. The steam produced by the first heat exchanger can be provided to the third heat exchanger together with the depressurized exhaust from the high pressure turbine 910 for further heating. The exhaust stream from the high pressure turbine is thus mixed with the output from the first heat exchanger 1202 (i.e., the lowest temperature heat exchanger) and sent to the third heat exchanger 1206. Note that the first and third heat exchangers are both considered low-pressure heat exchangers as they handle water/steam at a lower pressure than the second heat exchanger 1204 and the fourth heat exchanger 1208. After heating in the third heat exchanger, the superheated/reheated steam is sent to the low pressure turbine. The mass flow in the third heat exchanger may therefore be larger than that through the fourth heat exchanger, for example, four times as large.

During discharge, the thermal storage fluid flows from hot reservoir 906 to the fourth heat exchanger 1208. The thermal storage fluid then flows sequentially to the third heat exchanger 1206, to the second heat exchanger 1204, and to the first heat exchanger 1202 before returning to the cold reservoir 908. Thus, the operating temperature of each of the heat exchangers decreases in order from the further heat exchanger 1208 to the first heat exchanger 1202. The thermal storage system may have a maximum discharge rate that produces on the order of hundreds of MW_e, for example, 210 MW_e of electrical power. The thermal storage

system discharge rate can provide, for example, 507 MW_{th}. The thermal storage system may be capable of providing several hours of discharge, for example, 2.6 hours.

Steam produced for the high pressure turbine by the thermal storage system may have a temperature of 485 °C at a pressure of 210 bar and a flow rate of 155 kg/s (see A in FIG. 12C).

5 Steam produced for the low pressure turbine by the thermal storage system may have a temperature of 455 °C at a pressure of 74 bar and a flow rate of 205 kg/s (see C in FIG. 12C).

Feedwater provided to the first heat exchanger in the heat exchanger assembly can have a temperature of 200 °C at a pressure of 79 bar and a flow rate of 50 kg/s (see B in FIG. 12C).

10 Feedwater provided to the second heat exchanger in the heat exchanger assembly can have a temperature of 236 °C at a pressure of 224 bar and a flow rate of 155 kg/s (see E in FIG. 12C). Exhaust from the high pressure turbine can be at a temperature of 341 °C at a pressure of 76 bar and a flow rate of 155 kg/s (see D in FIG. 12C).

During periods of relatively high insolation (i.e., when the solar load of the solar collection system is 80% or greater of maximum continuous rating of the system), enthalpy in
15 the thermal storage system can be used to boost supercritical steam production by insolation. In such a configuration, the thermal storage system may operate in series, as shown in FIG. 12D. After the initial heating of the pressurized feedwater 940 in the second heat exchanger 1204, the pressurized steam can be directed to fourth heat exchanger 1208. For example, the temperature of the superheated steam exiting the fourth heat exchanger 1208 can be less than 350° C, 300°
20 C, or less. The output of the fourth heat exchanger 1208 can be directed to the solar receiver 904, wherein insolation heats the output to generate a supercritical fluid, e.g., supercritical steam. The supercritical steam can be used to drive high pressure turbine 910 to generate useful work. Depressurized exhaust from the high pressure turbine 910 can be reheated in the solar receiver by insolation and used to drive low pressure turbine 912 to produce useful work.

25 Since the low pressure heat exchanger module 1250 is not required in this configuration, the thermal storage fluid may bypass the first heat exchanger 1202 and the third heat exchanger 1206 of the module 1250 as it flows from the hot reservoir 906 to the cold reservoir. Accordingly, the thermal storage fluid would only flow from the hot reservoir through the high pressure heat exchanger module 1255 (i.e., through the fourth heat exchanger 1208 and then
30 through the second heat exchanger 1204) to the cold reservoir. Alternatively, the thermal storage fluid can continue to flow through the first and third heat exchangers even though substantially no enthalpy transfer may be occurring therein.

During periods of relatively low insolation (i.e., when the solar load of the solar collection system is between 20% and 80% of maximum continuous rating of the system),

enthalpy in the thermal storage system can be used to provide a system boost by concurrent steam production with insolation. In such a configuration, the thermal storage system may operate in parallel, as shown in FIG. 12E.

Low pressure feedwater can be fed into the first heat exchanger 1202 and high pressure feedwater 940 can be fed into the second heat exchanger 1204 while the thermal storage system discharges (i.e., while thermal storage fluid flows from the hot reservoir 906 to the cold reservoir 908 by way of the heat exchangers 1202-1208). The output from the first and second heat exchangers can be fed to the third heat exchanger 1206 and fourth heat exchanger 1208, respectively, where further heating may occur resulting in respective low pressure and high pressure steam outputs. The high pressure steam may be superheated (e.g., have a temperature of about 485 °C) but at a pressure less than the critical point of water (e.g., at a pressure of less than about 210 bar). Steam produced using insolation in solar receiver 904 can be combined with the steam from the fourth heat exchanger 1208. The steam produced by the solar receiver may also be subcritical due to the low or declining insolation levels.

However, use of this mode of operation may only be available once the pressure of the steam from the solar receiver 904 matches the pressure of the steam from fourth heat exchanger 1208 (e.g., 210 bar). If the solar collection system is producing steam having a greater pressure than that exiting the heat exchanger, the solar collection system can operate in sliding pressure mode until the two pressures are the same, after which the pressure is maintained at the common pressure. While the solar collection system and the heat exchanger may produce steam at the same pressure, the temperatures of the steam may be at different temperatures. Appropriate mechanisms can be used to combine the different temperature steam flows prior to introduction to the high pressure turbine.

The steam from both the solar receiver 904 and the fourth heat exchanger 1208 can be used to drive high pressure turbine 910 to generate useful work. As with other configurations, depressurized exhaust from the high pressure turbine 910 can be provided to inlet 942 of solar receiver 904 for reheating. The exhaust reheated using insolation by solar receiver 904 can be combined with the steam from the third heat exchanger 1206 to drive low pressure turbine 912 to generate useful work.

In one or more embodiments, substantially all of the supercritical fluid generated in supercritical steam generator is sent to heat exchanger assembly to heat a thermal storage fluid of the solar energy storage system via conduction and/or convection instead of using any of the supercritical steam to immediately generate electricity.

Although the above discussion pertains to using water as the working/solar fluid, other embodiments may relate to other working/solar fluids, such as, but not limited to pressurized carbon dioxide (CO₂).

In some embodiments, the heat exchange process within any of the heat exchanger(s) disclosed herein may be a substantially isobaric process (e.g., at least with respect to the water/steam side of the heat exchanger) in any of the charging and/or discharging phases. For example, the pressure of the supercritical steam produced using insolation can be less than 500 bar, 400 bar, 350 bar, or less, but still above the critical point for water. In one or more embodiments, one or more (i.e., any combination of) of the temperature features, turbine features, and/or fluid quantity features disclosed herein may be combined.

For example, where the working fluid of the solar collection system is at a pressure P and flows through the heat exchanger assembly at the pressure P for enthalpy transfer with the thermal storage system, one or more of the following features may be provided:

- (i) the temperature T_1 of the cold reservoir is above the melting point of the storage fluid (i.e., in liquid phase) but below the phase change temperature (e.g., boiling temperature or supercritical temperature) at the pressure P – for example, by at least 5°, 10°, 20°, 30°, 50°, 75°, 100°, 150° C or more and/or at most 200°, 150°, 100°, 75°, 50°, 30°, 20°, 10° C or less;
- (ii) the temperature T_2 of the hot reservoir is below the boiling point of the thermal storage fluid and/or the temperature of the hot reservoir T_2 exceeds the phase change temperature at the pressure P by least 25°, 50°, 100°, 150°, 200°, 250°, 300° C or more;
- (iii) the pressure P is at least 50 bar, 75 bar, 100 bar, 125 bar, 150 bar or higher and/or below 300 bar, 250 bar, 200 bar, or less
- (iv) the power capacity of the turbine is at least 1 MW, 5MW, 10MW, 50MW, 100MW, 250MW, 500MW, or more.

During the discharge phase of operation, the thermal storage fluid at a single phase may serve two purposes: (i) provide latent heat to effect a phase change to the working fluid for the solar collection system and (ii) provide sensible heat to further heat the working fluid after the phase change, for example, to superheat saturated or supercritical steam.

Although specific pressures, temperatures, and flow rates have been disclosed herein, these are exemplary values only and deviations from the specific values as well as completely different values for the pressures, temperatures, and flow rates can also be used according to one or more contemplated embodiments. In addition, the working fluid and/or thermal storage materials are not limited to those fluids and/or materials specifically disclosed herein. Rather,

the teachings of the present disclosure find application to a wide variety of working fluids and/or thermal storage materials.

In one or more embodiments, the thermal storage system can include a control system, either as a shared component with the solar collection system and the electricity generation system (i.e., as part of an overall system controller) or a separate module particular to the thermal storage system (i.e., independent from but potentially interactive with other control modules). The control system can be configured to regulate flow of thermal storage medium within and between the different storage reservoirs. For example, the control system can regulate a rate of media flow between the reservoirs, a timing of the flow, an allocation parameter governing relative quantities of media in the reservoirs, or any other aspect governing the distribution of thermal storage medium within the system. The flow parameters can be governed in accordance with heat transfer parameters of the flow path between reservoirs. For example, the flow parameters can be based, at least in part, on the heat transfer parameters of the heat exchanger, a temperature of the solar fluid flowing through the heat exchanger, a flow rate of the solar fluid flowing through the heat exchanger, or any other aspects or conditions affecting the heat transfer between the thermal storage system and the solar fluid.

The control system can be configured to control other aspects of the overall system, including, for example, one or more parameters of the solar fluid. For example, the control system can be configured to regulate the temperature and/or flow rate of the solar fluid, at least partly in thermal communication with the heat exchanger. Moreover, the control system may regulate the flow of the solar fluid through the one or more heat exchangers, for example, to insure that the solar fluid does not fully condense after the enthalpy exchange with the thermal storage fluid during charging and/or to insure that the solar fluid fully condenses after the enthalpy exchange with the liquid-phase solar fluid input to the solar collection system. The control system can include any combination of mechanical or electrical components for accomplishing its goals, including but not limited to motors, pumps, valves, analog circuitry, digital circuitry, software (i.e., stored in volatile or non-volatile computer memory or storage), wired or wireless computer network(s) or any other necessary component or combination of component to accomplish its goals.

The temperature of the thermal storage medium can also be monitored within any of the thermal storage reservoirs or combination thereof. The temperature of the solar fluid after heat exchange with the thermal storage system can also be monitored. The control system can regulate flow parameters according to one or more of these measured temperatures. For example, the control system can use the measure temperatures and regulate responsively thereto

in order to ensure that the temperature(s) of the solar fluid after heat exchange with the thermal storage system is at or above the boiling point temperature of the solar fluid. The measurement can be accomplished by any device known in the art. For example, the measurement can be direct (e.g., using a thermocouple or infrared sensor) or indirect (e.g., measuring a temperature in a location indicative of fluid temperature within a conduit or reservoir).

The teachings disclosed herein can be useful for increasing solar energy generation efficiency during days of intermittent cloudy periods, maximizing electricity production and/or revenue generation of a solar electric facility, and/or meeting reliability requirements of an electric transmission network operator.

Various embodiments described herein relate to insolation and solar energy. However, this is just one example of a source of intermittent energy. The teachings herein can be applied to other forms of intermittent energy as well, according to one or more contemplated embodiments. Steam can be generated by other sources of energy and used to charge a thermal storage system. For example, fossil fuels, electricity heaters, nuclear energy, or any other source could be used to generate steam for thermal storage. Although aspects of the present disclosure relate to the production of steam using insolation for the production of electricity, it is also contemplated that the teachings presented herein can be applied to solar thermal systems that convert insolation into any of a heated working fluid, mechanical work, and electricity. Although panel-type heliostats with a central solar tower are discussed above, the teachings of the present disclosure are not limited thereto. For example, redirection and/or concentration of insolation for heating a working fluid can be accomplished using an elongated trough reflector.

Although various embodiments of the thermal storage system are explained in terms of a specific case where the number of reservoirs is two, it is noted that fewer or greater than two reservoirs can also be used according to one or more contemplated embodiments. Moreover, some of the examples discussed herein relate to a single-phase thermal storage system for a multi-phase power generation systems. However, the teachings presented herein are not to be so limited. Rather, the teachings presented herein can be applicable to multi-phase thermal storage systems according to one or more contemplated embodiments. Moreover, while specific examples have been discussed with respect to using water/steam as a solar fluid, it is further contemplated that other solar fluids can be used as well. For example, salt-water and/or pressurized carbon dioxide can be used as a solar fluid. Other solar fluids are also possible according to one or more contemplated embodiments. In addition, while specific examples have been discussed with respect to using molten salt and/or molten metal as the thermal storage medium, it is contemplated that other types of thermal storage media can be used as well.

It will be appreciated that the modules, processes, systems, and sections described above can be implemented in hardware, hardware programmed by software, software instruction stored on a non-transitory computer readable medium or a combination of the above. A system for controlling the thermal storage system, the solar collection system, and/or the electricity
5 generating system can be implemented, for example, using a processor configured to execute a sequence of programmed instructions stored on a non-transitory computer readable medium. The processor can include, but is not limited to, a personal computer or workstation or other such computing system that includes a processor, microprocessor, microcontroller device, or is comprised of control logic including integrated circuits such as, for example, an Application
10 Specific Integrated Circuit (ASIC). The instructions can be compiled from source code instructions provided in accordance with a programming language such as Java, C++, C#.net or the like. The instructions can also comprise code and data objects provided in accordance with, for example, the Visual Basic™ language, or another structured or object-oriented programming language. The sequence of programmed instructions and data associated therewith can be stored
15 in a non-transitory computer-readable medium such as a computer memory or storage device which can be any suitable memory apparatus, such as, but not limited to read-only memory (ROM), programmable read-only memory (PROM), electrically erasable programmable read-only memory (EEPROM), random-access memory (RAM), flash memory, disk drive, etc.

Furthermore, the modules, processes, systems, and sections can be implemented as a
20 single processor or as a distributed processor. Further, it should be appreciated that the steps discussed herein can be performed on a single or distributed processor (single and/or multi-core). Also, the processes, modules, and sub-modules described in the various figures of and for embodiments above can be distributed across multiple computers or systems or can be co-located in a single processor or system. Exemplary structural embodiment alternatives suitable
25 for implementing the modules, sections, systems, means, or processes described herein are provided below, but not limited thereto. The modules, processors or systems described herein can be implemented as a programmed general purpose computer, an electronic device programmed with microcode, a hard-wired analog logic circuit, software stored on a computer-readable medium or signal, an optical computing device, a networked system of electronic
30 and/or optical devices, a special purpose computing device, an integrated circuit device, a semiconductor chip, and a software module or object stored on a computer-readable medium or signal, for example. Moreover, embodiments of the disclosed method, system, and computer program product can be implemented in software executed on a programmed general purpose computer, a special purpose computer, a microprocessor, or the like.

Embodiments of the method and system (or their sub-components or modules), can be implemented on a general-purpose computer, a special-purpose computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element, an ASIC or other integrated circuit, a digital signal processor, a hardwired electronic or logic circuit such as a discrete element circuit, a programmed logic circuit such as a programmable logic device (PLD), programmable logic array (PLA), field-programmable gate array (FPGA), programmable array logic (PAL) device, etc. In general, any process capable of implementing the functions or steps described herein can be used to implement embodiments of the method, system, or a computer program product (software program stored on a non-transitory computer readable medium).

Furthermore, embodiments of the disclosed method, system, and computer program product can be readily implemented, fully or partially, in software using, for example, object or object-oriented software development environments that provide portable source code that can be used on a variety of computer platforms. Alternatively, embodiments of the disclosed method, system, and computer program product can be implemented partially or fully in hardware using, for example, standard logic circuits or a very-large-scale integration (VLSI) design. Other hardware or software can be used to implement embodiments depending on the speed and/or efficiency requirements of the systems, the particular function, and/or particular software or hardware system, microprocessor, or microcomputer being utilized. Embodiments of the method, system, and computer program product can be implemented in hardware and/or software using any known or later developed systems or structures, devices and/or software by those of ordinary skill in the applicable art from the function description provided herein and with a general basic knowledge of solar collection, thermal storage, electricity generation, and/or computer programming arts.

Features of the disclosed embodiments can be combined, rearranged, omitted, etc., within the scope of the invention to produce additional embodiments. Furthermore, certain features can sometimes be used to advantage without a corresponding use of other features.

It is thus apparent that there is provided in accordance with the present disclosure, system, methods, and devices for thermal storage. Many alternatives, modifications, and variations are enabled by the present disclosure. While specific embodiments have been shown and described in detail to illustrate the application of the principles of the present invention, it will be understood that the invention can be embodied otherwise without departing from such principles. Accordingly, Applicants intend to embrace all such alternatives, modifications, equivalents, and variations that are within the spirit and scope of the present invention.

CLAIMS

1. A method of generating electricity comprising:

(a) during a first operating period:

(a1) producing supercritical steam using insolation on a solar receiver, the supercritical
5 steam having a temperature and pressure greater than the critical point of water;

(a2) driving a first turbine using a first portion of the supercritical steam to generate
electricity;

(a3) driving a second turbine using exhaust from the first turbine to generate electricity;
and

10 (a4) co-flowing a second portion of the supercritical steam with a thermal storage fluid
along respective flowpaths through a heat exchanger such that enthalpy in the supercritical
steam second portion is transferred to the flowing thermal storage fluid; and

(b) during a second operating period:

(b1) flowing pressurized feedwater together with the thermal storage fluid along the
15 respective flowpaths through the heat exchanger such that a first portion of the enthalpy in the
thermal storage fluid is transferred to the pressurized feedwater so as to produce superheated
steam;

(b2) driving the first turbine using the superheated steam to generate electricity; and

(b3) flowing the exhaust from the first turbine through a reheat heat exchanger together
20 with the thermal storage fluid such that a second portion of the enthalpy in the thermal storage
fluid heats the exhaust; and

(b4) driving the second turbine using the heated exhaust from the reheat heat exchanger
to generate electricity.

2. The method of claim 1, wherein:

25 (b3) includes:

flowing feedwater together with the thermal storage fluid along respective flowpaths
through another heat exchanger such that a third portion of the enthalpy in the thermal storage
fluid is transferred to the feedwater so as to produce low pressure steam;

combining the low pressure steam with the exhaust from the first turbine; and

30 flowing the combination of the low pressure steam and the exhaust through the reheat
heat exchanger together with the thermal storage fluid such that the second portion of the
enthalpy in the thermal storage fluid heats the combination, and

in (b4) the second turbine uses the heated combination from the reheat heat exchanger to
generate electricity.

3. The method of claim 1, wherein the thermal storage fluid includes at least one of a molten salt and a molten metal.

4. The method of claim 1, wherein the flowing in (b1) is such that the thermal storage fluid remains above a melting temperature thereof.

5. The method of claim 1, wherein the flowing in (b1) is in a reverse direction along the respective flowpaths from that in (a4).

6. The method of claim 1, wherein the co-flowing in (a4) is such that the supercritical steam second portion is condensed into pressurized water.

7. The method of claim 1, further comprising (a5) flowing the exhaust from the first turbine through the solar receiver so as to reheat the exhaust using insolation, wherein in (a3) the second turbine uses the reheated exhaust from the solar receiver to generate electricity.

8. The method of claim 1, wherein the heat exchanger includes a high temperature section and a low temperature section, the reheat heat exchanger being arranged in the thermal storage fluid flowpath between the high and low temperature sections.

9. The method of claim 1, wherein the first operating period corresponds to relatively high insolation on the solar receiver and the second operating period corresponds to relatively low or no insolation on the solar receiver.

10. The method of claim 1, wherein (b4) includes:

producing steam using an auxiliary boiler and combining with the heated exhaust from the reheat heat exchanger; and

driving the second turbine using the combined exhaust and steam to generate electricity.

11. The method of claim 1, further comprising:

(c) during a third operating period:

(c1) flowing pressurized feedwater together with the thermal storage fluid along the respective flowpaths through the heat exchanger such that the enthalpy in the thermal storage fluid is transferred to the pressurized feedwater so as to produce steam;

(c2) further heating the steam from the heat exchanger using insolation on the solar receiver to generate supercritical steam;

(c3) driving the first turbine using the supercritical steam from the solar receiver to generate electricity; and

(c4) driving the second turbine using the exhaust from the first turbine to generate electricity.

12. The method of claim 11, further comprising (c5) flowing the exhaust from the first turbine through the solar receiver so as to reheat the exhaust using insolation, wherein in (c4) the second turbine uses the reheated exhaust from the solar receiver to generate electricity.

13. The method of claim 11, wherein the third operating period corresponds to a period of relatively high insolation on the solar receiver and when a thermal storage system containing the thermal storage fluid is fully charged.

14. The method of claim 1, further comprising:

(d) during a fourth operating period:

(d1) producing steam using insolation on the solar receiver;

(d2) flowing pressurized feedwater together with the thermal storage fluid along the respective flowpaths through the heat exchanger such that enthalpy in the thermal storage fluid is transferred to the pressurized feedwater so as to produce steam;

(d3) combining the steam produced in (d1) with the steam produced in (d2) and driving the first turbine using the combined steam to generate electricity; and

(d4) driving the second turbine using the exhaust from the first turbine to generate electricity.

15. The method of claim 14, wherein the steam produced in (d2) is at a same pressure as the steam produced in (d1), the pressures being less than the critical point for water.

16. The method of claim 1, wherein the first and second turbines are on a same shaft used to drive a generator in producing said electricity.

17. The method of claim 14, further comprising (d5) flowing the exhaust from the first turbine through the solar receiver so as to reheat the exhaust using insolation, wherein in (d4) the second turbine uses the reheated exhaust from the solar receiver to generate electricity.

18. The method of claim 14, wherein the fourth operating period corresponds to a period of low or diminishing insolation on the solar receiver.

19. A system for generating electricity comprising:

a solar collection system constructed to produce supercritical steam using insolation;

a thermal storage system having first and second thermal storage reservoirs for holding a thermal storage fluid therein;

an electricity generating system having first and second turbines, each turbine being configured to generate electricity using steam provided thereto, the first turbine being constructed to accept steam at supercritical temperature and pressure, an outlet of the first turbine being operatively coupled to an inlet of the second turbine;

a heat exchanger system by which the solar collection system and the thermal storage system are thermally coupled to each other such that enthalpy in one of the solar collection system and the thermal storage system can be transferred to the other; and

a control system that operates the solar collection, thermal storage, electricity generating, and heat exchanger systems, the control system being configured to control the systems such that:

during a first operating mode, a thermal storage fluid flows from the first reservoir to the second reservoir by way of the heat exchanger system such that enthalpy in a portion of the supercritical steam produced by the solar collection system is transferred to the flowing thermal storage fluid while the remainder of the supercritical steam is used by the first turbine to generate electricity; and

during a second operating mode, the thermal storage fluid flows from the second reservoir to the first reservoir by way of the heat exchanger system such that enthalpy in the thermal storage fluid heats pressurized feedwater to produce superheated steam, the first turbine using the superheated steam to generate electricity.

20. The system of claim 19, wherein during the first operating mode, the inlet of the second turbine is operatively coupled to the outlet of the first turbine through the solar collection system, which heats exhaust from the first turbine outlet as it flows to the second turbine inlet.

21. The system of claim 19, wherein during the second operating mode, the inlet of the second turbine is operatively coupled to the outlet of the first turbine through the heat exchanger system, which heats exhaust from the first turbine outlet as it flows to the second turbine inlet.

22. The system of claim 19, wherein the solar collection system includes a solar receiver and a plurality of heliostats constructed to reflect insolation onto the solar receiver.

23. The system of claim 19, wherein the thermal storage fluid includes one of a molten metal and a molten salt.

24. The system of claim 19, wherein the heat exchanger system includes a heat exchanger having a first section and a second section, a thermal storage fluid inlet of the first section being connected to the first thermal storage reservoir and a thermal storage fluid outlet of the second section being connected to the second thermal storage reservoir.

25. The system of claim 24, wherein the heat exchanger system further includes a reheat heat exchanger connecting a thermal storage fluid outlet of the first section of the heat exchanger to a thermal storage fluid inlet of the second section of the heat exchanger.

26. The system of claim 25, wherein, during the second operating mode the reheat heat exchanger transfers enthalpy from the thermal storage medium, which flows between the heat

exchanger first section and the heat exchanger second section, to exhaust from the first turbine outlet so as to heat the exhaust prior to introduction to the second turbine inlet.

27. The system of claim 24, wherein the heat exchanger is a tube and shell type heat exchanger.

5 28. The system of claim 19, wherein the heat exchanger system includes a first set of heat exchangers and a second set of heat exchangers, the first set of heat exchangers operating at a higher pressure than the second set of heat exchangers.

29. The system of claim 28, wherein during the second mode of operation:

10 the first set of heat exchangers transfers enthalpy from the thermal storage fluid flowing therethrough to generate steam at a first pressure for use by the first turbine in generating electricity;

the second set of heat exchangers transfers enthalpy from the thermal storage fluid flowing therethrough to generate steam at a second pressure for use by the second turbine in generating electricity; and

15 the second pressure is less than the first pressure.

30. The system of claim 19, further comprising an auxiliary boiler coupled to the second turbine inlet for providing supplemental steam thereto during the second operating mode.

31. A method for generating electricity comprising:

20 (a) using insolation to generate supercritical steam, the supercritical steam having a temperature and pressure in excess of the critical point of water;

(b) storing enthalpy from a portion of the supercritical steam in a thermal storage fluid while simultaneously driving a first turbine with the remaining supercritical steam to generate electricity and driving a second turbine with reheated exhaust from the first turbine; and

(c) after the storing, performing at least one of:

25 (c1) using the stored enthalpy to produce superheated steam from pressurized feedwater, and driving the first turbine with the superheated steam to generate electricity;

(c2) using the stored enthalpy to produce steam from pressurized feedwater, using insolation to further heat the produced steam, and driving the first turbine with the further heated steam to generate electricity; and

30 (c3) using stored enthalpy to produce steam while also using insolation to produce steam, combining the steam produced using enthalpy and insolation, and driving either the first or second turbine with the combined steam to generate electricity.

32. The method of claim 31, wherein (b) includes:

using insolation to reheat exhaust from the first turbine; and

driving the second turbine with the reheated exhaust to generate electricity.

33. The method of claim 31, wherein (c1) includes using the stored enthalpy to reheat exhaust from the first turbine and driving a second turbine with the reheated exhaust to generate electricity.

5 34. The method of claim 33, further comprising:

(d) using stored enthalpy to generate low pressure steam from pressurized feedwater; and

(e) supplementing the exhaust from the first turbine with the low pressure steam from (d) prior to the reheating in (c1).

10 35. The method of claim 33, wherein the reheating exhaust occurs in a low-pressure portion of a heat exchange assembly and the producing superheated steam occurs in a high-pressure portion of the heat exchange assembly, the thermal storage fluid passing through both the low-pressure and high-pressure portions of the heat exchange assembly.

36. The method of claim 35, wherein:

the low-pressure portion includes first and third heat exchangers;

15 the high-pressure portion includes second and fourth heat exchangers;

in (b), the heat exchangers are connected in parallel;

in (c1) and (c3), thermal storage fluid flowpaths of the heat exchangers are connected in series, water/steam flowpaths of the first and third heat exchangers are connected in series, and water/steam flowpaths of the second and fourth heat exchangers are connected in series; and

20 in (c2), the thermal storage fluid flowpaths of the second and fourth heat exchangers are connected in series, and the water/steam flowpaths of the second and fourth heat exchangers are connected in series.

37. A method of generating electricity from insolation and/or thermal storage fluid, the method comprising:

25 (a) at a first time:

(a1) using insolation to generate supercritical steam from pressurized liquid water;

(a2) subjecting a first portion of the supercritical steam to a heat transfer operation whereby enthalpy of the supercritical steam is conductively or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the supercritical steam to a second temperature;

30 (a3) using a second portion of the supercritical steam to drive a steam turbine to generate electricity;

(b) at a second time:

(b1) transferring enthalpy from the thermal storage fluid at the first temperature to pressurized liquid feedwater to generate superheated steam at a same pressure as the liquid feedwater and to cool the thermal storage fluid; and

(b2) using the superheated steam to drive the steam turbine to generate electricity.

5 38. The method of claim 37, wherein the thermal storage fluid is a molten salt or molten metal.

39. The method of claim 37, wherein, in (a2), the supercritical steam cooled to the second temperature condenses the steam into sub-cooled water.

10 40. The method of claim 39, wherein the pressurized liquid water in (a1) is produced from the sub-cooled water mixed with feedwater.

41. The method of claim 40, wherein the mixture of the sub-cooled water with feedwater is fed to a supercritical steam generator which uses the insolation to generate the supercritical steam in (a1).

15 42. The method of claim 37, wherein the heat transfer operation in (a2) is performed in a once-through heat exchanger.

43. The method of claim 42, wherein the heat exchanger is a tube and shell type heat exchanger.

44. A method of generating electricity from insolation and/or thermal storage fluid, the method comprising:

20 (a) at a first time:

(a1) using insolation to generate supercritical steam from pressurized liquid water;

(a2) subjecting a first portion of the supercritical steam to a heat transfer operation whereby enthalpy of the supercritical steam is conductively or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the
25 supercritical steam to a second temperature;

(a3) using a second portion of the supercritical steam to drive a steam turbine to generate electricity;

(b) at a second time:

30 (b1) transferring enthalpy from the thermal storage fluid to pressurized liquid feedwater at a first pressure to produce saturated steam at the first pressure;

(b2) transferring enthalpy from the thermal storage fluid to low-pressure steam at a second pressure obtained from the steam turbine so as to further heat the low-pressure steam, the second pressure being less than the first pressure; and

(b3) transferring enthalpy from the thermal storage fluid to saturated steam at the first pressure to produce superheated steam.

45. The method of claim 44, wherein (b2) includes using the heated low-pressure steam to drive another steam turbine to generate electricity.

5 46. The method of claim 44, wherein (b3) includes using the superheated steam to drive the steam turbine to generate electricity.

47. The method of claim 44, wherein (b1) through (b3) take place in different heat exchanger portions with the thermal storage fluid passing through each of the heat exchanger portions, the heat exchanger portion associated with (b3) operating at a higher temperature than the heat
10 exchanger portion associated with (b2), which operates at a higher temperature than the heat exchanger portion associated with (b1).

48. The method of claim 44, wherein the thermal storage fluid includes a molten salt or molten metal.

49. The method of claim 44, wherein at least a portion of the saturated steam at the first
15 pressure in (b3) is produced in (b1).

50. A system for electricity generation comprising:

a first solar receiver in which pressurized feedwater is heated to generate supercritical steam by insolation;

a thermal energy storage system including hot and cold reservoirs of a sensible heat storage
20 liquid; and

a heat exchanger assembly having one or more heat exchangers, the heat exchanger assembly being constructed to transfer heat between the supercritical steam and the sensible heat storage liquid during charging of the thermal energy storage system and between the sensible heat storage liquid and pressurized water and/or steam during discharging of the thermal energy
25 storage system.

51. The system of claim 50, wherein the sensible heat storage liquid includes one of molten salt and a molten metal.

52. The system of claim 50, wherein each heat exchanger is a once-through vertical heat exchanger.

30 53. The system of claim 52, wherein each heat exchanger is a tube and shell type heat exchanger.

54. The system of claim 50, further comprising a second solar receiver in which pressurized steam is superheated by insolation.

55. The system of claim 50, wherein during discharging:

a first of the heat exchangers is constructed such that the sensible heat storage liquid is in thermal communication with saturated steam at a first pressure so as to produce superheated steam;

5 a second of the heat exchangers is constructed such that the sensible heat storage liquid is in thermal communication with steam at a second pressure obtained from a steam turbine, the second pressure being less than the first pressure; and

a third of the heat exchangers is constructed such that the sensible heat storage liquid is in thermal communication with pressurized liquid feedwater so as to produce saturated steam at the first pressure.

10 56. A method of generating electricity from insolation and/or a thermal storage fluid, the method comprising:

(a) at a first time:

(a1) using insolation to generate supercritical steam from pressurized liquid water;

15 (a2) subjecting a first portion of the supercritical steam to a heat transfer operation whereby enthalpy of the supercritical steam is conductively or convectively transferred to a thermal storage fluid to heat the thermal storage fluid to a first temperature and to cool the supercritical steam to a second temperature;

(a3) using a second portion of the supercritical steam to drive a first steam turbine to generate electricity;

20 (b) at a second time:

(b1) transferring enthalpy from the thermal storage fluid to liquid feedwater at a first pressure to generate superheated steam at the first pressure;

(b2) transferring enthalpy from the thermal storage fluid to liquid feedwater at a second pressure to generate superheated steam at the second pressure, the second pressure being less
25 than the first pressure,

(b3) using the superheated steam at the first pressure to drive the first steam turbine to generate electricity; and

(b4) using the superheated steam at the second pressure to drive a second steam turbine to generate electricity.

30 57. The method of claim 56, wherein:

(b1) includes transferring enthalpy from the thermal storage fluid to the liquid feedwater with the thermal storage fluid at a third temperature and then transferring enthalpy with the thermal storage fluid at the first temperature, the first temperature being greater than the third temperature; and

(b2) includes transferring enthalpy from the thermal storage to the liquid feedwater with the thermal storage fluid at a fourth temperature and then transferring enthalpy with the thermal storage fluid at a second temperature, the second temperature being greater than the fourth temperature.

5 58. The method of claim 57, wherein the first temperature is greater than the second temperature, and the third temperature is greater than the fourth temperature.

59. A system for generating electricity comprising:

a first solar receiver in which pressurized feedwater is heated to generate supercritical steam using insolation;

10 a thermal energy storage system including hot and cold reservoirs for a sensible heat storage liquid; and

a heat exchanger assembly including at least four heat exchangers, the heat exchanger assembly being constructed to transfer heat between the supercritical steam and the sensible heat storage liquid during charging of the thermal energy storage system and between the sensible
15 heat storage liquid and pressurized water during discharging of the thermal energy storage system,

wherein at least two of the heat exchangers are constructed to operate at a different pressure than the other heat exchangers.

20 60. The system of claim 59, wherein the at least two heat exchangers are constructed to operate and accept high pressure water at a first pressure, at least one other heat exchanger is constructed to operate and accept low pressure water at a second pressure, and the first pressure is greater than the second pressure.

61. The system of claim 60, wherein the second pressure is less than 100 bar and the first pressure is at least 200 bar.

25 62. The system of claim 61, wherein the second pressure is less than 80 bar and the first pressure is at least 220 bar.

63. The system of claim 59, wherein each heat exchanger is a once-through vertical heat exchanger.

30 64. The system of claim 63, wherein each heat exchanger is a tube and shell type heat exchanger.

65. The system of claim 59, further comprising a second solar receiver in which pressurized steam is superheated using insolation.

66. The system of claim 59, wherein during discharging:

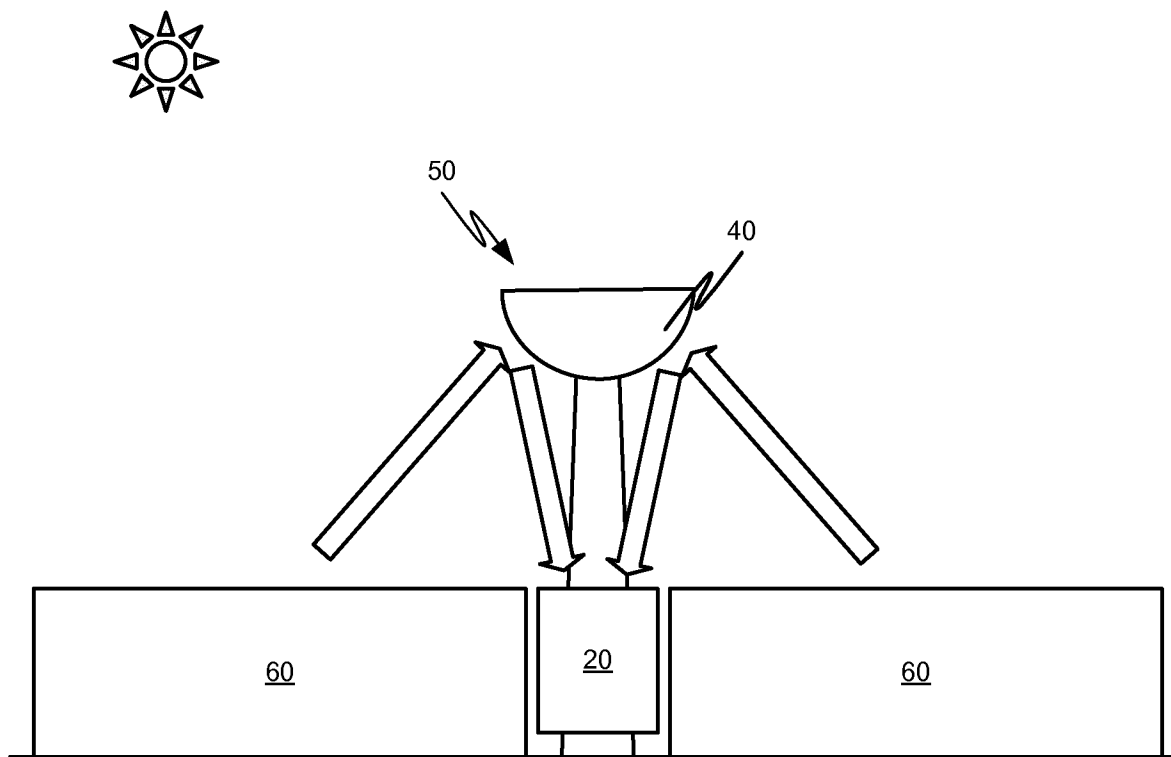
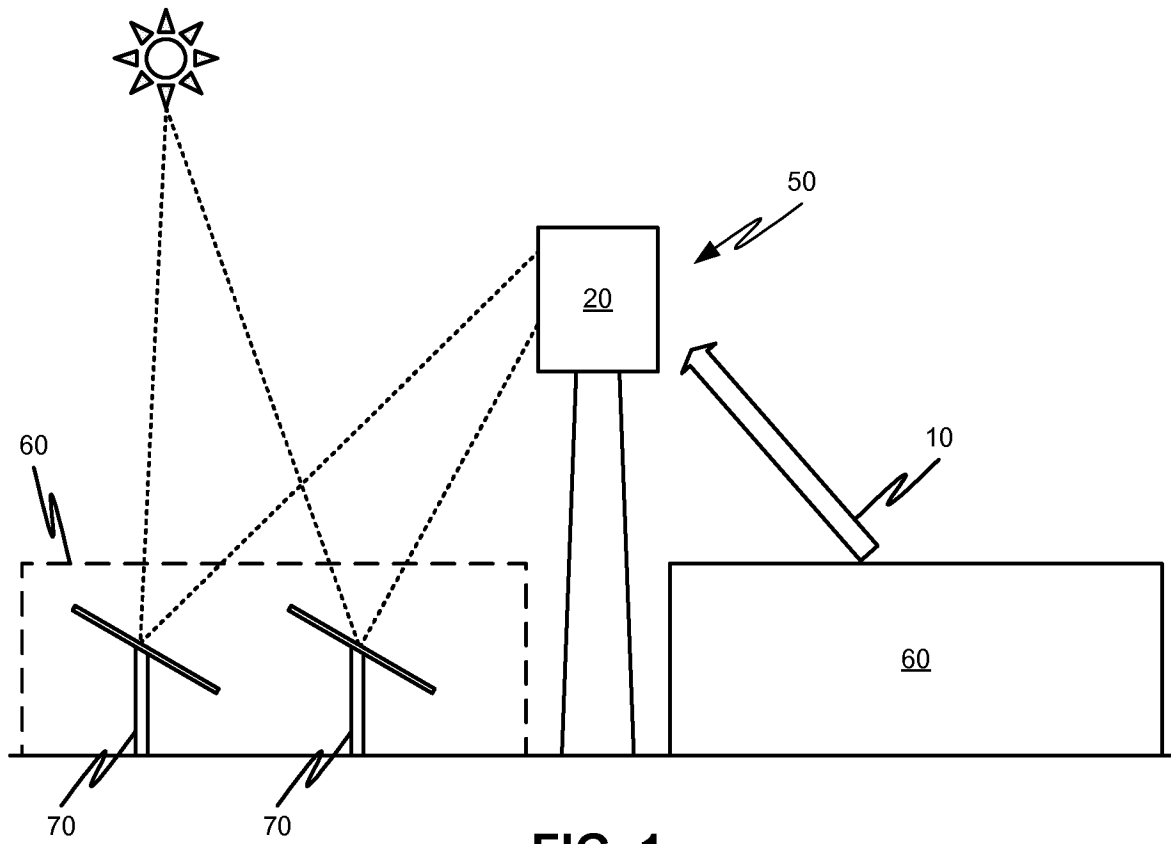
a first heat exchanger is constructed such that the heat storage liquid is in thermal communication with high pressure steam so as to produce high pressure superheated steam;

a second heat exchanger is constructed such that the heat storage liquid is in thermal communication with low pressure steam so as to produce low pressure superheated steam;

5 a third heat exchanger is constructed such that the heat storage liquid is in thermal communication with high pressure liquid feedwater so as to produce high pressure steam; and

a fourth heat exchanger is constructed such that the heat storage liquid is in thermal communication with low pressure liquid feedwater so as to produce low pressure steam.

10 67. The system of claim 66, wherein the first and third heat exchangers are in fluid communication such that the first heat exchanger receives the steam from the third heat exchanger, and the second and fourth heat exchangers are in fluid communication such that the second heat exchanger receives the steam from the fourth heat exchanger.



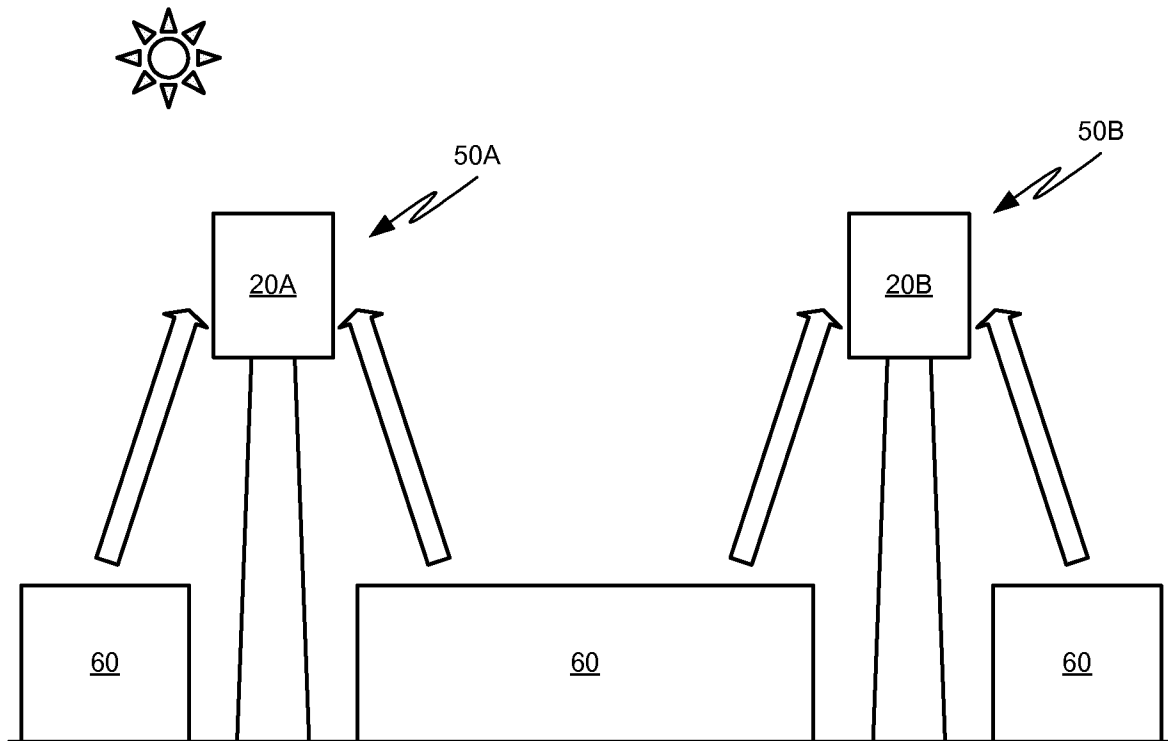


FIG. 3

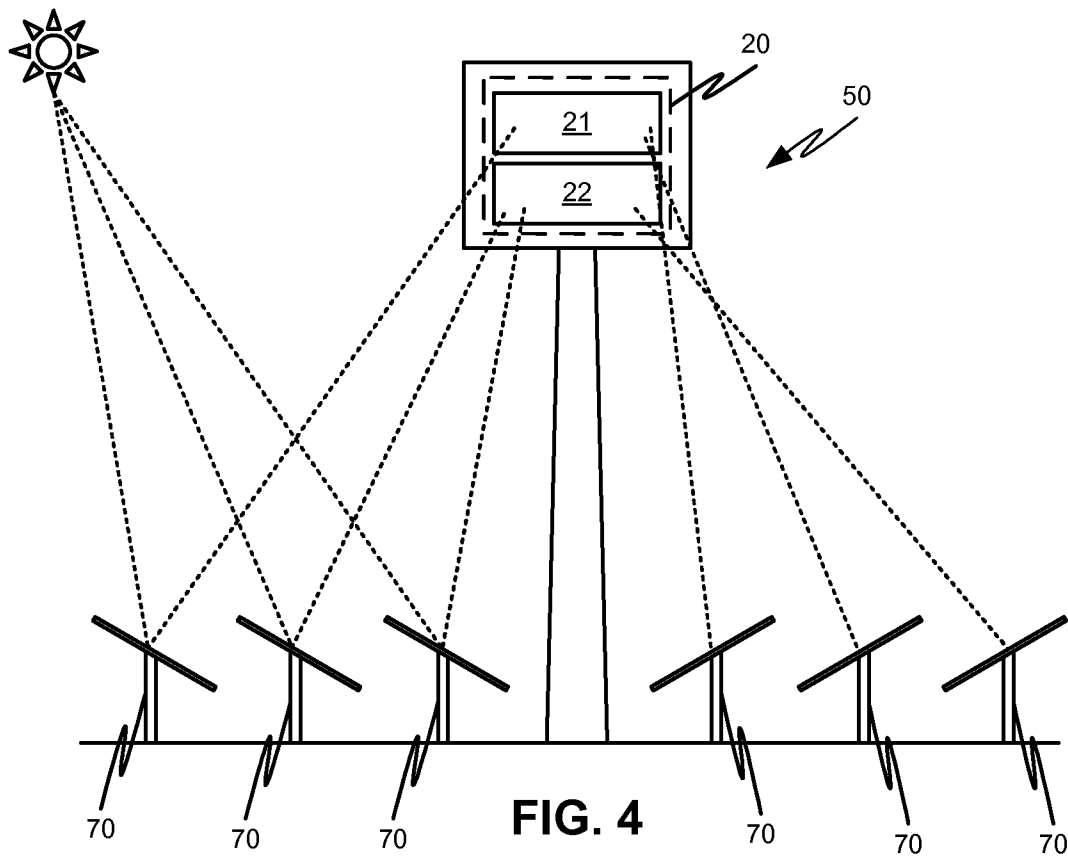


FIG. 4

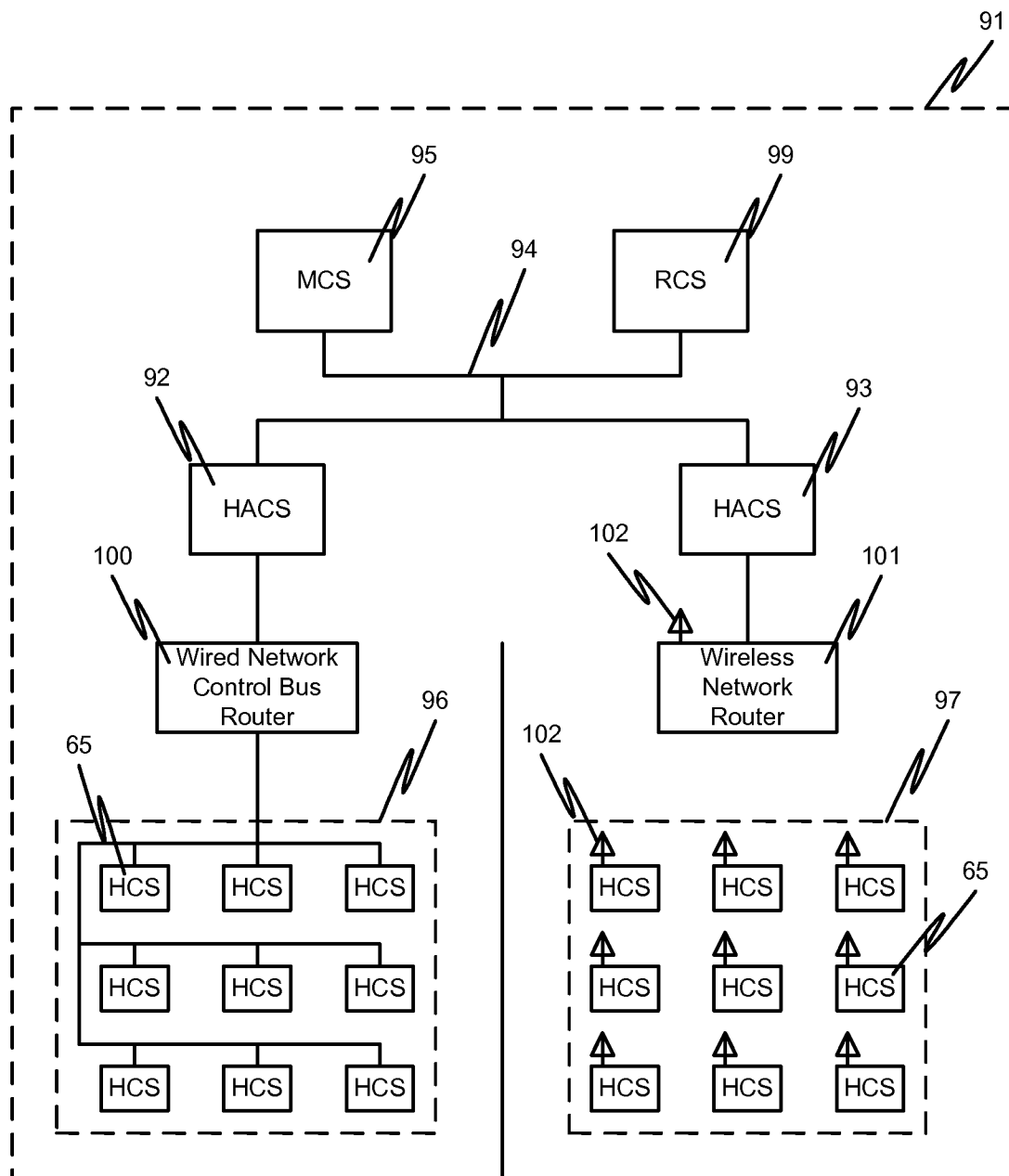


FIG. 5

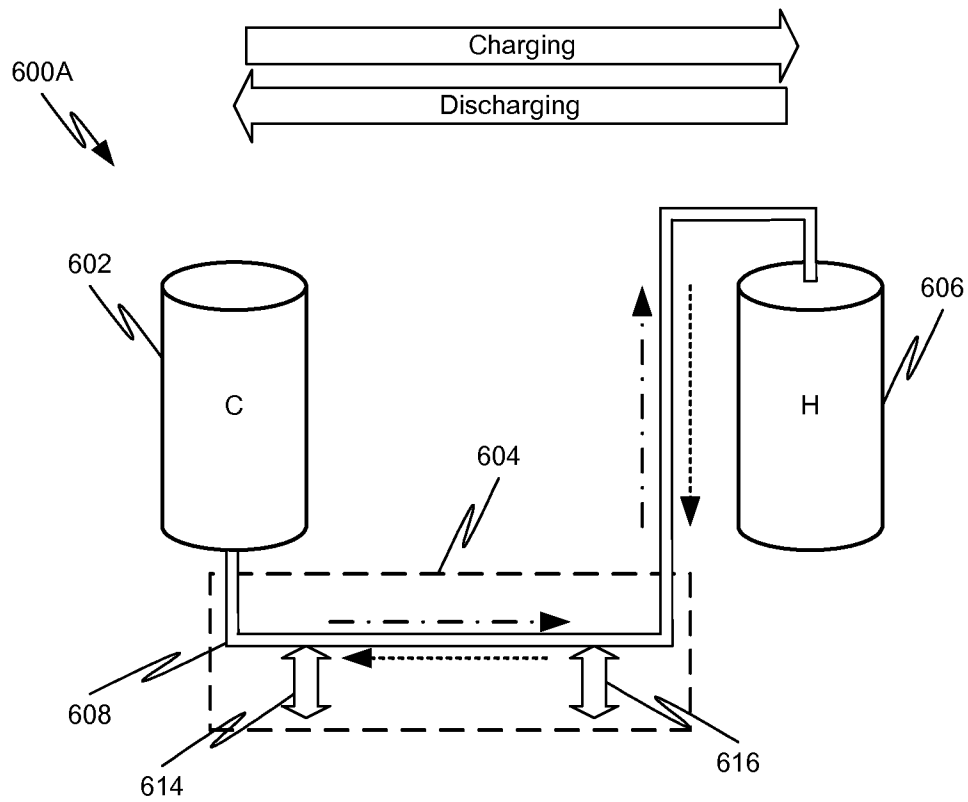


FIG. 6A

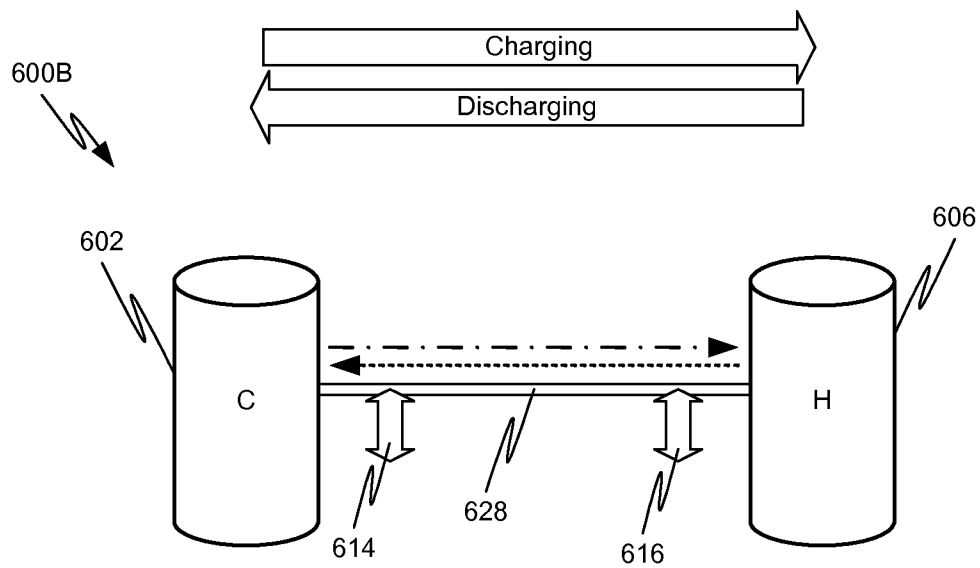
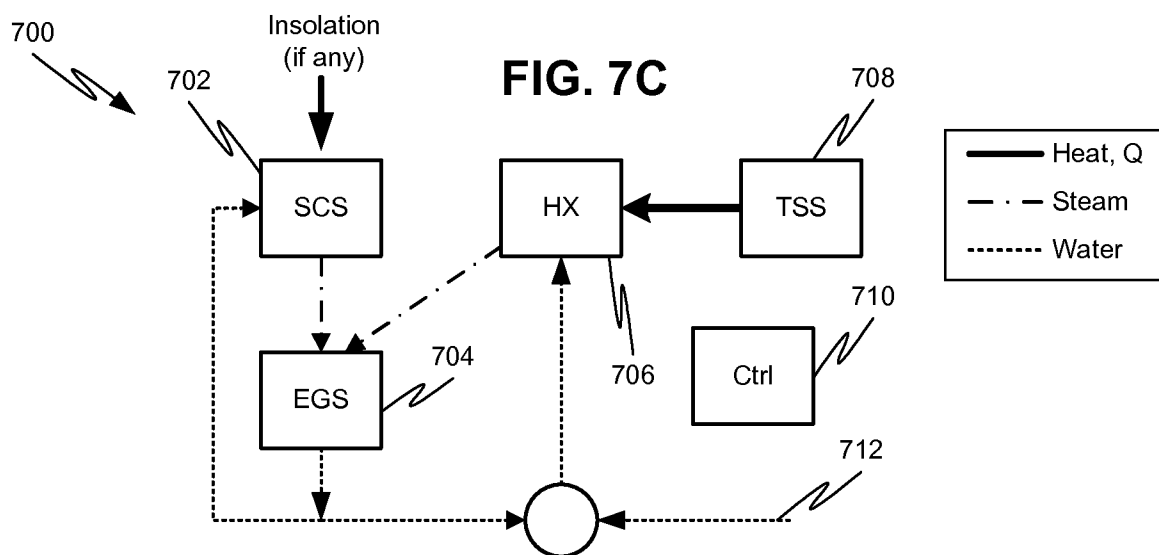
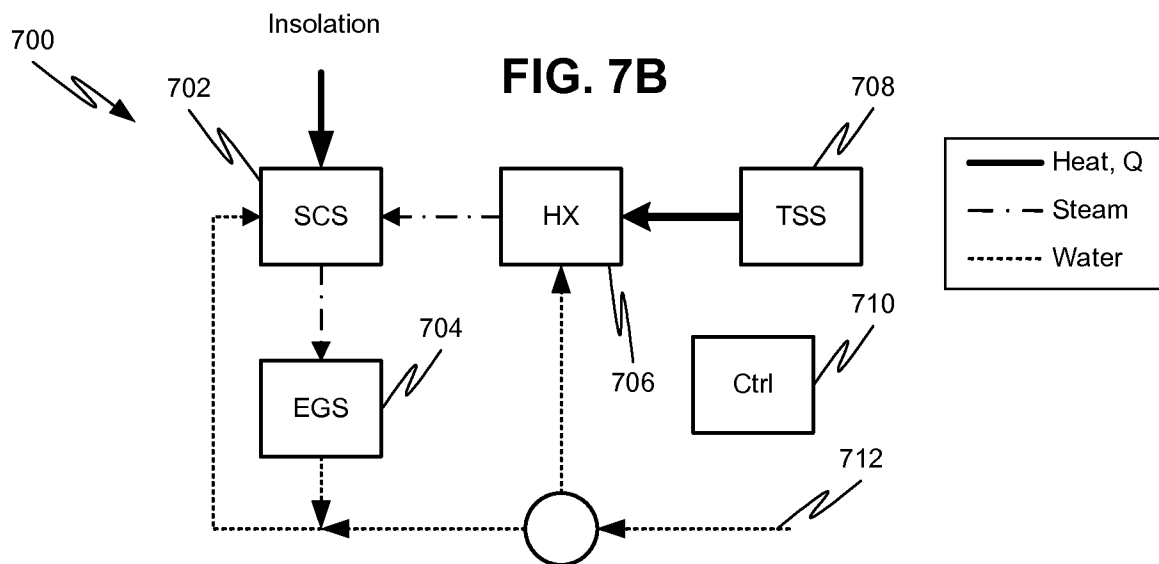
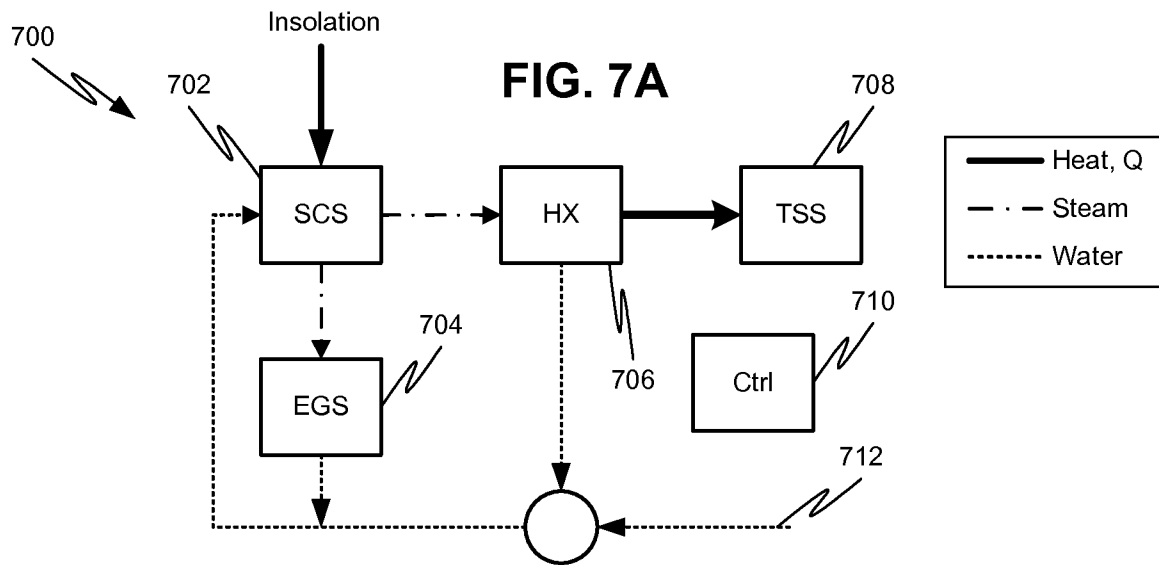


FIG. 6B



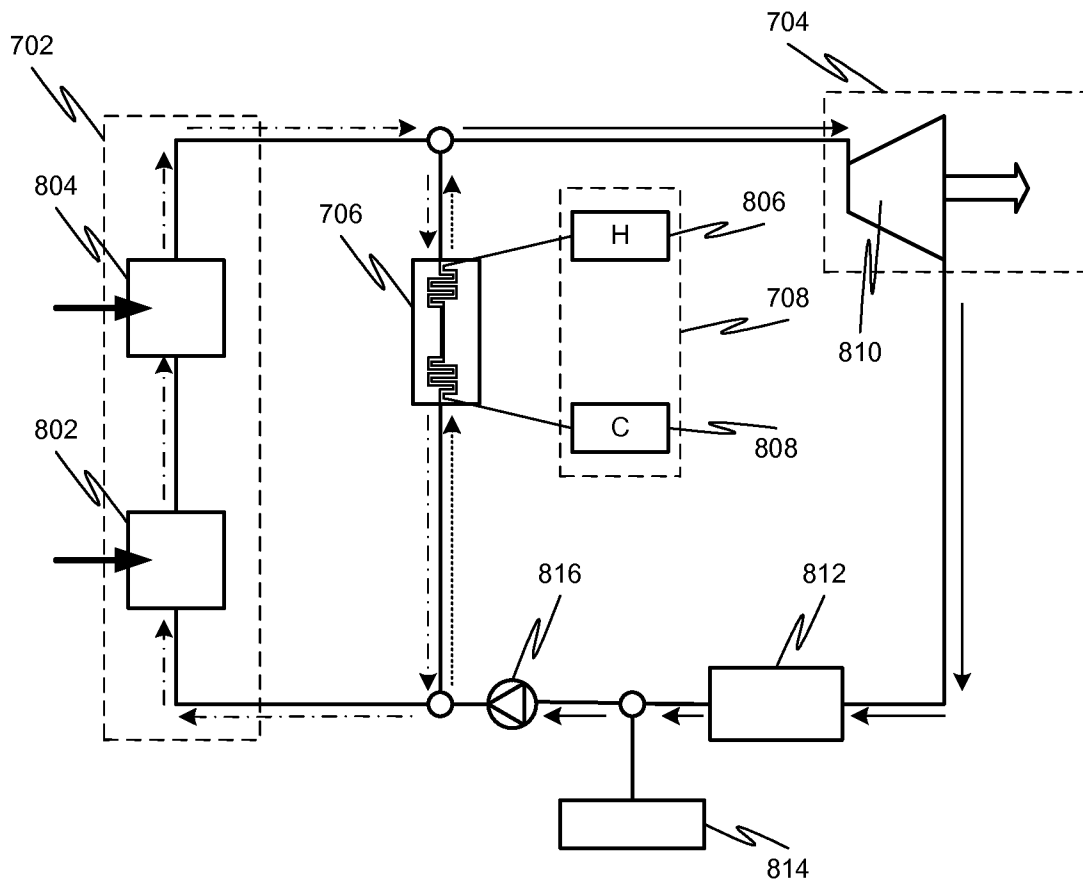


FIG. 8

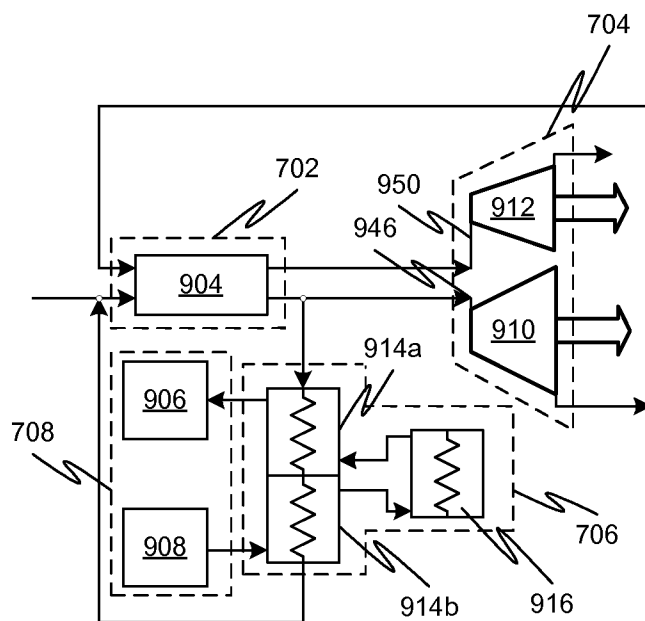


FIG. 9A

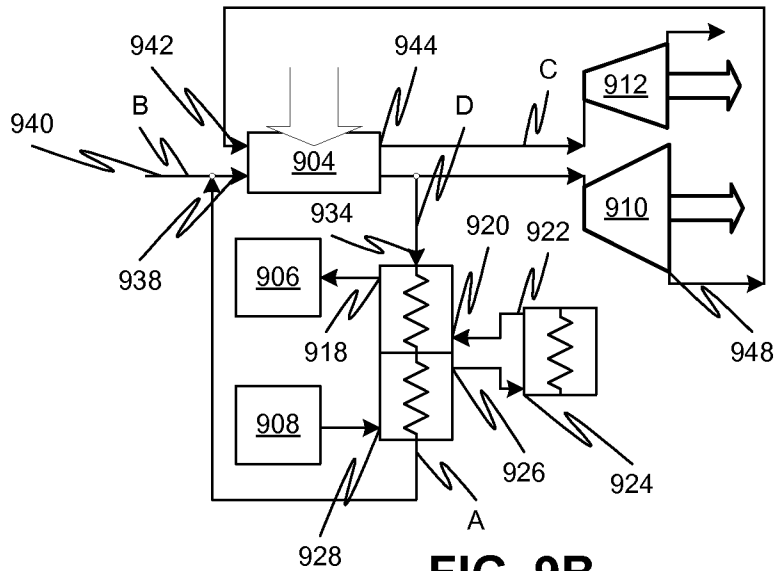


FIG. 9B

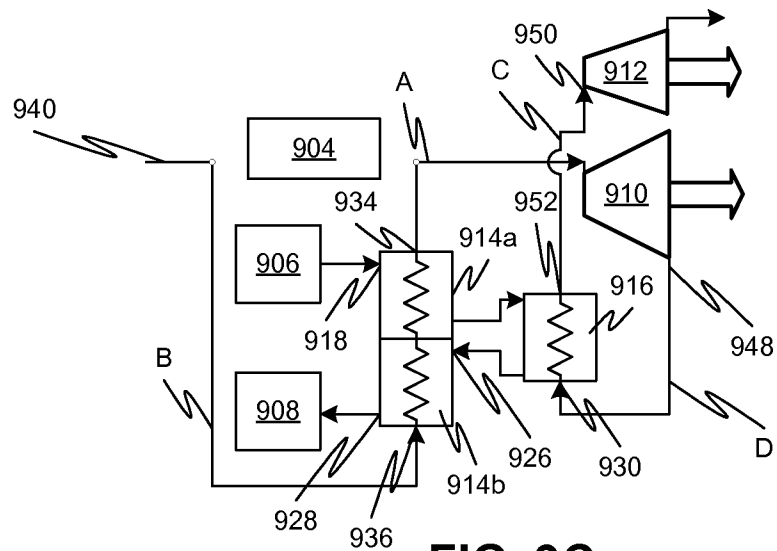


FIG. 9C

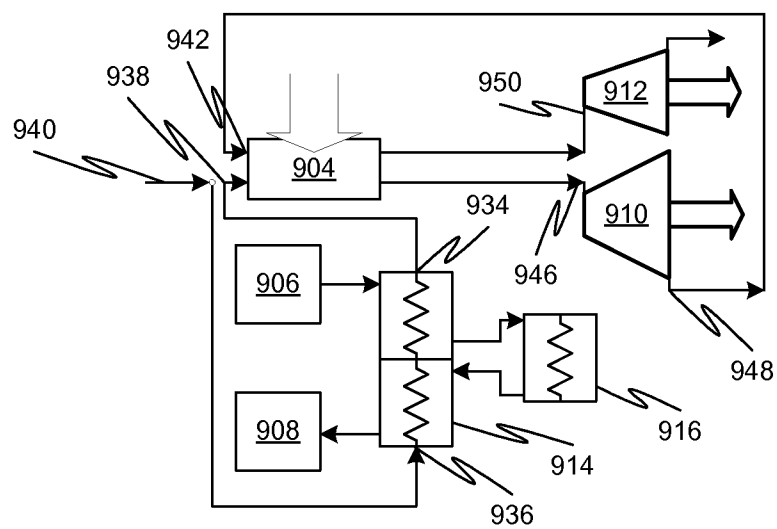


FIG. 9D

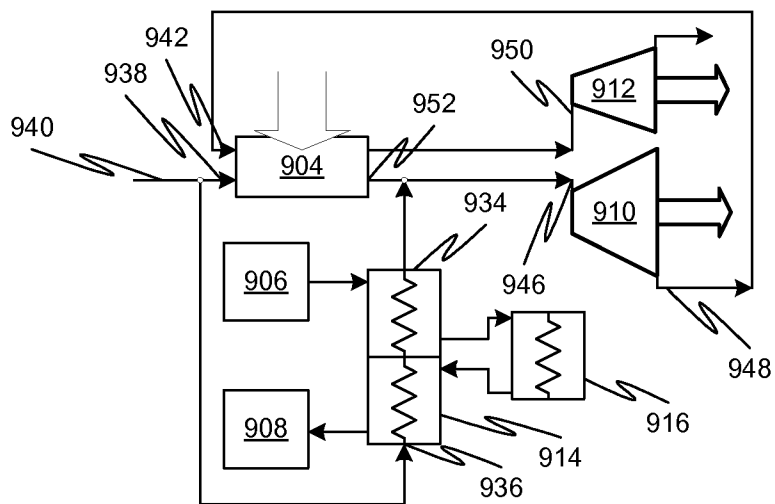


FIG. 9E

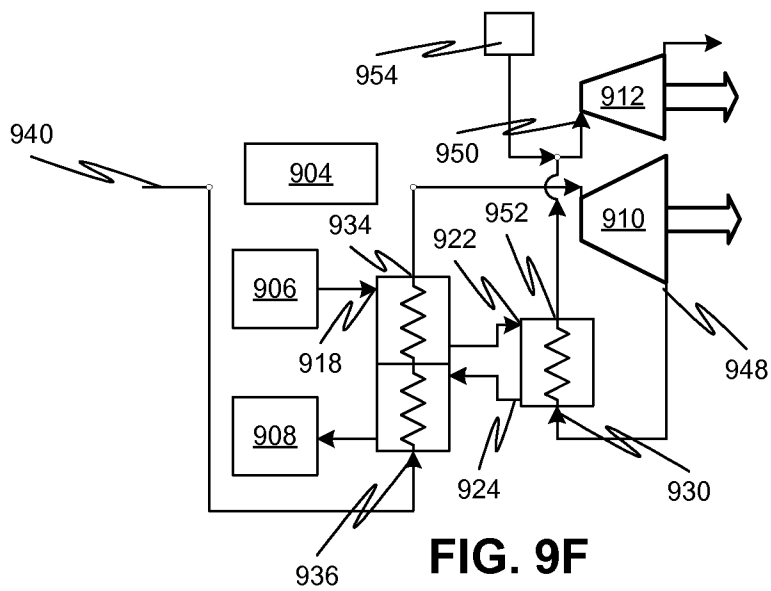


FIG. 9F

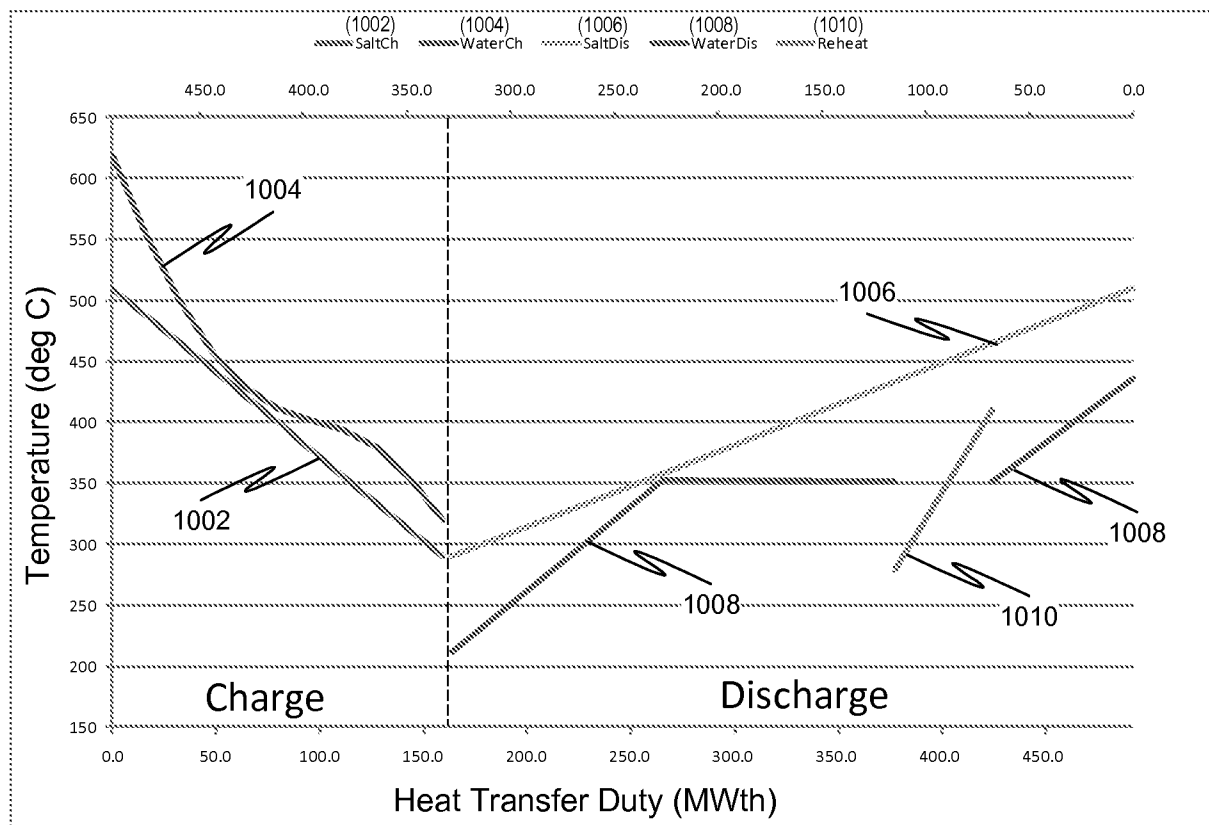


FIG. 10

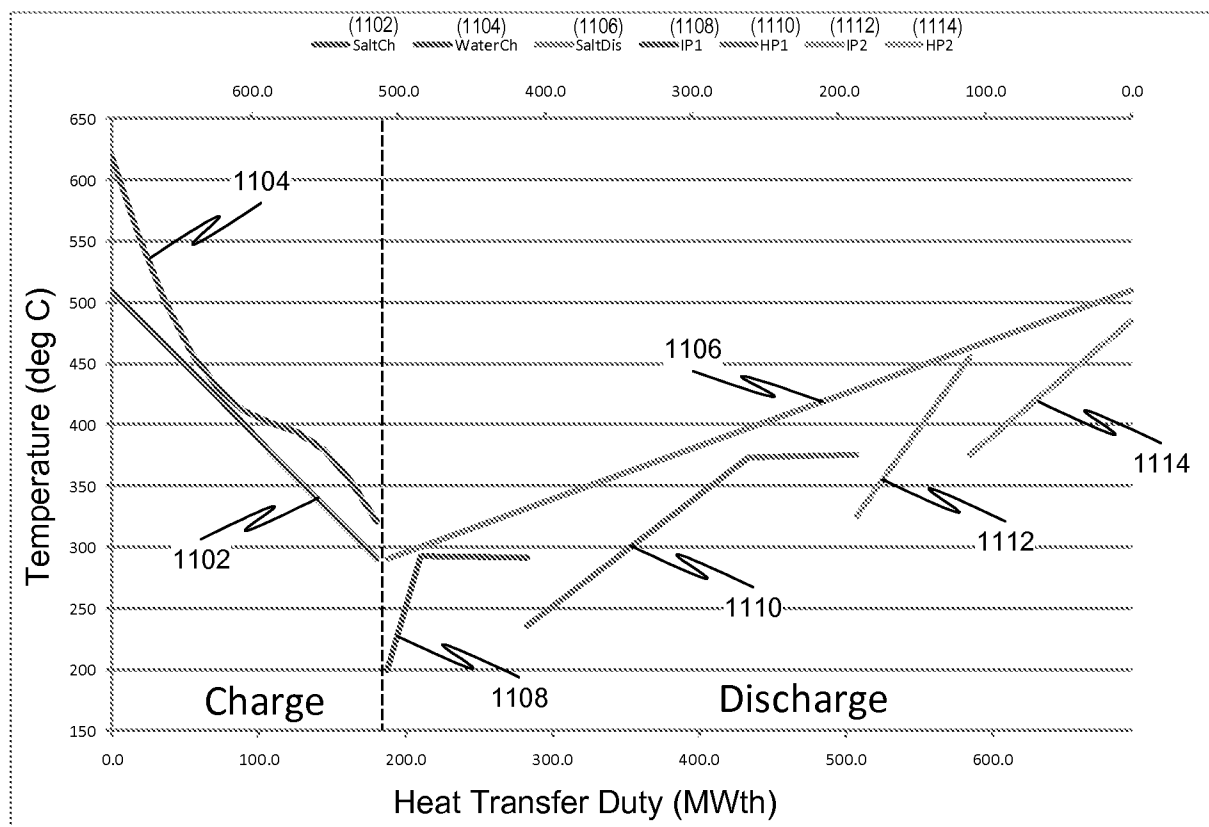


FIG. 11

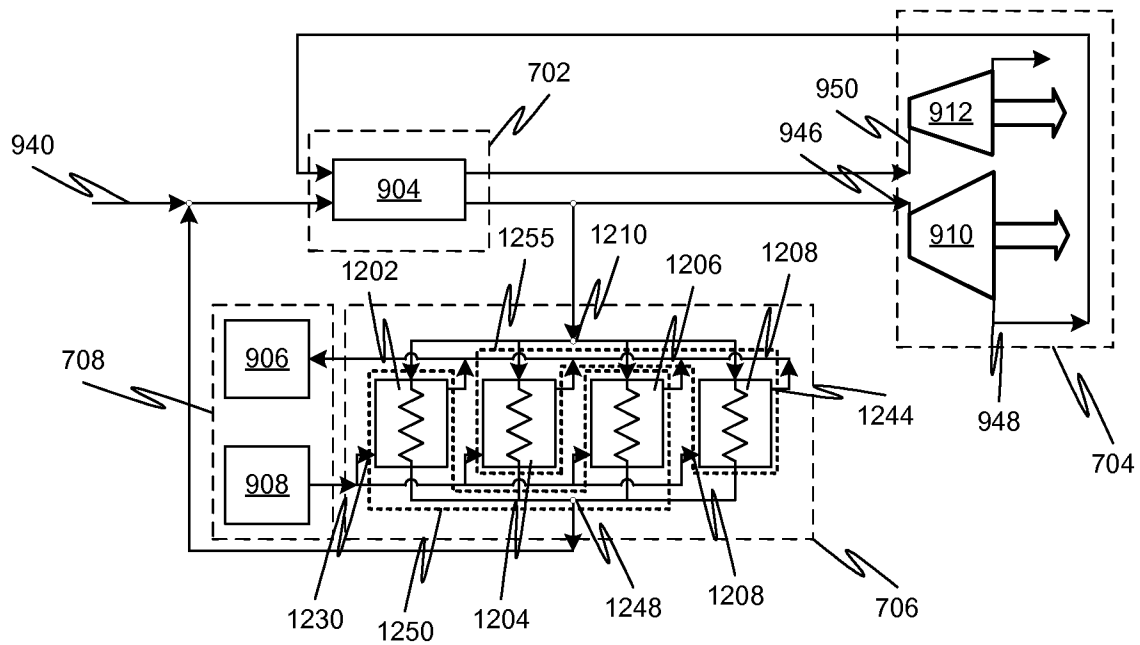


FIG. 12A

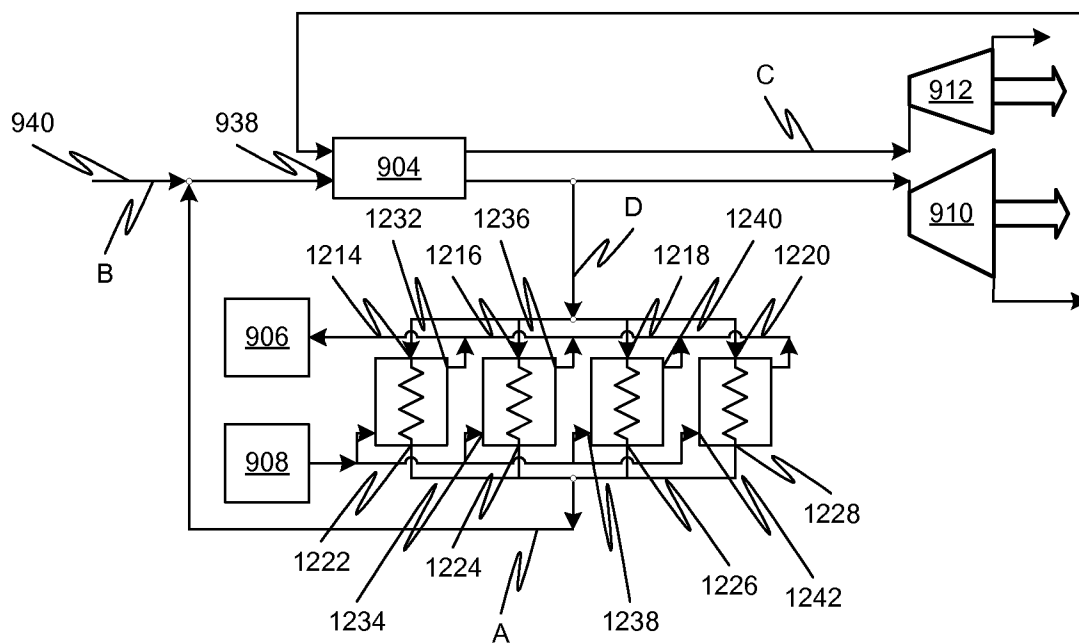


FIG. 12B

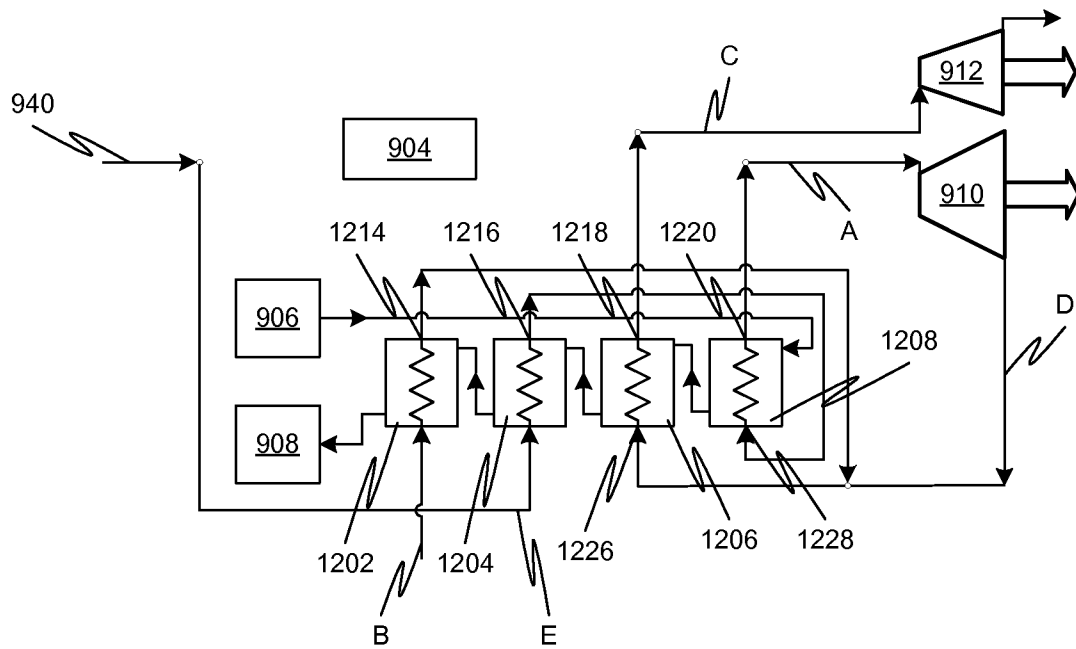


FIG. 12C

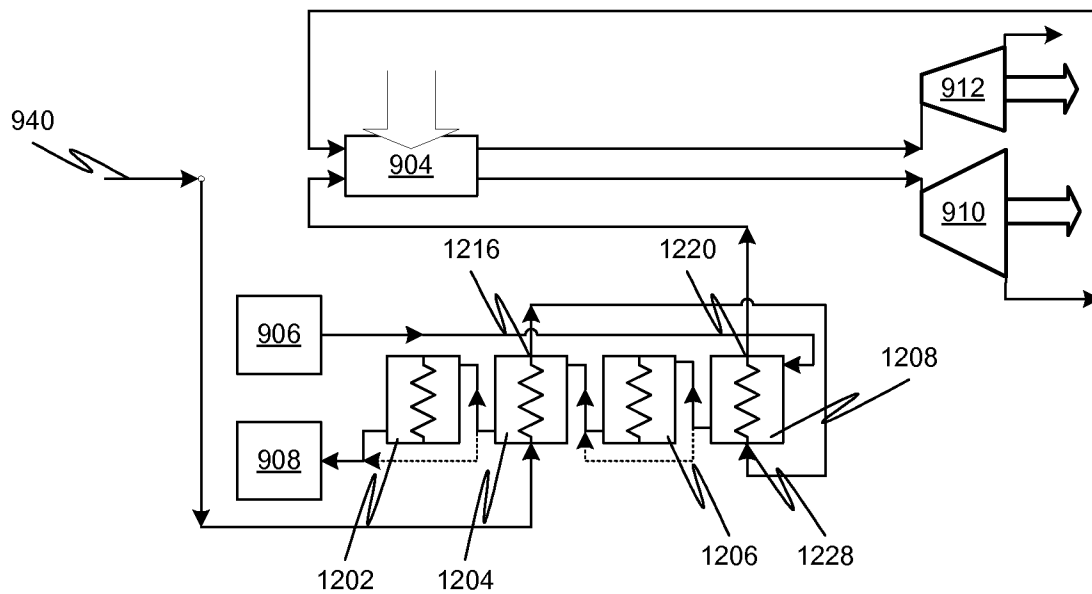


FIG. 12D

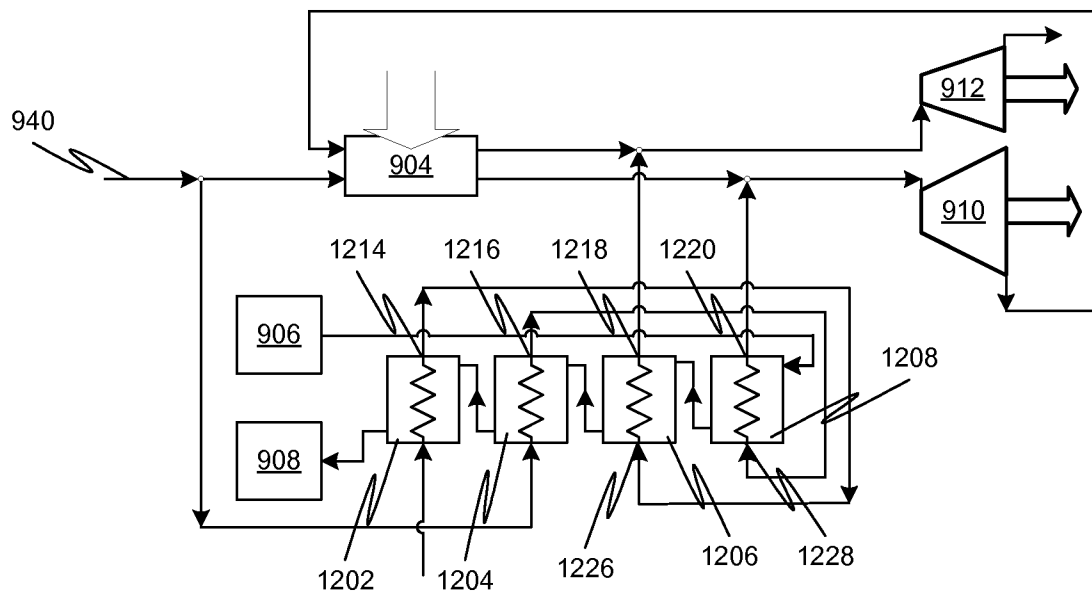


FIG. 12E

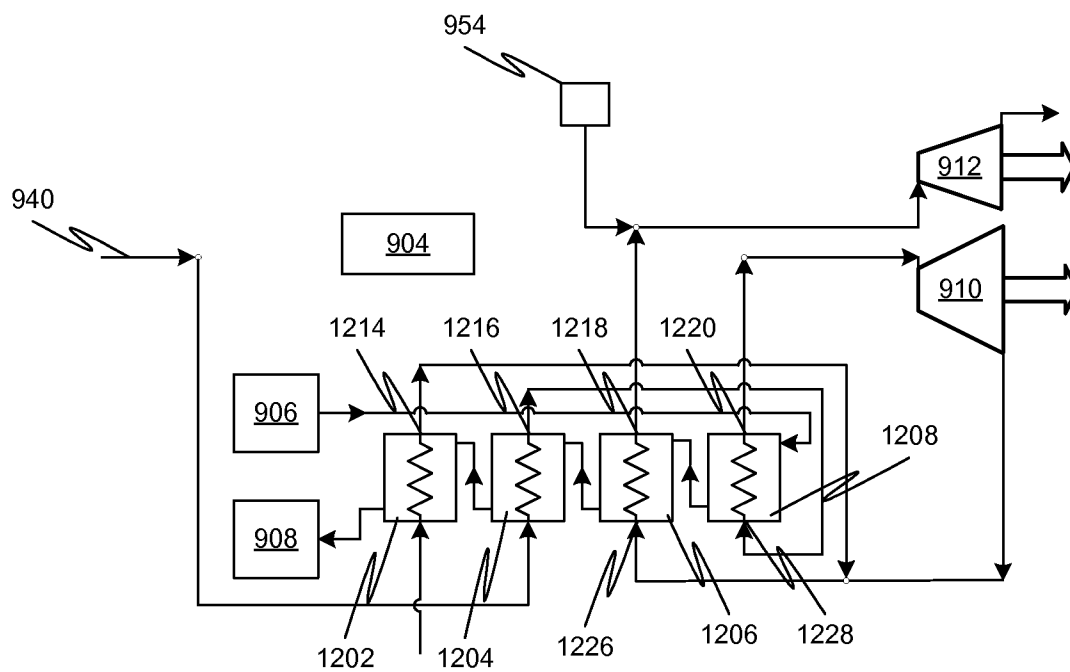


FIG. 12F