(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 October 2019 (31.10.2019)

WIPO | PCT

(10) International Publication Number
WO 2019/204943 A1

(51) International Patent Classification:
F24F 5/00 (2006.01) *F24F 12/00* (2006.01) *F24D 11/02* (2006.01) *F24F 13/30* (2006.01) *F24D 3/12* (2006.01)

(21) International Application Number: PCT/CA2019/050545

(22) International Filing Date: 26 April 2019 (26.04.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/662,953 26 April 2018 (26.04.2018) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

(54) **Title:** BUILDING ENERGY SYSTEM

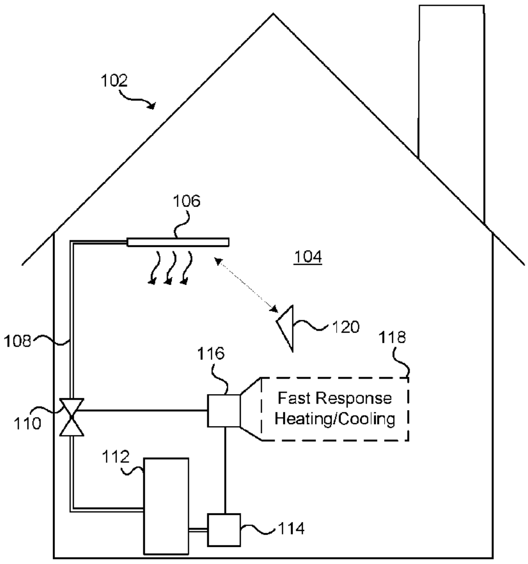

FIG. 1

(57) **Abstract:** The present disclosure describes equipment, methods, and systems for energy efficient buildings. In accordance with some aspects of the present disclosure, a building energy system is disclosed that comprises a plurality of homes and a central server that is configured to match supply and demand of electricity consumption from non-fossil fuel sources. In the building energy system, each of the plurality of homes comprise a home controller that can communicate with the central server over a communication network. The plurality of homes further comprise several sub-systems and equipment that further reduce energy consumption and integrate with the home controller to reduce GHGs associated with electricity consumption.

WO 2019/204943 A1

BUILDING ENERGY SYSTEM

RELATED APPLICATIONS

[0001] The current disclosure claims priority of US Provisional Application 62/662,953 Filed April 26, 2018, the entire contents of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to equipment, systems, and methods for an energy-efficient building, and in particular to improving energy efficiency by reducing reliance on electricity produced using fossil fuels.

BACKGROUND

[0003] Buildings require energy inputs for heating and cooling. Improved building materials and techniques have improved the heat efficiency of buildings and reduced energy consumption. However, even though a building may consume less energy it may be consuming electricity from the electrical grid at times when the electricity is being produced by fossil fuel sources and not at times that sufficient zero-emissions generation is available.

[0004] With climate change, the priority is not simply to reduce energy consumption but to reduce greenhouse gas emissions (GHGs). Accordingly, equipment, systems, and methods that reduce the greenhouse gas emissions associated with the energy consumption of a building remains highly desirable.

SUMMARY

[0005] In accordance with the present disclosure there is provided an energy efficient building heating, ventilation and air conditioning (HVAC) system, comprising: a thermal energy storage system comprising a hot storage section and a cold storage section; an electric heat pump for heating the hot storage section of the thermal energy storage system and cooling the cold storage section of the thermal energy storage system; and a fast response radiant hydronic heating/cooling system to circulate a heat transfer liquid heated or cooled by the thermal energy storage system.

[0006] In accordance with the present disclosure there is further provided a thermal storage system comprising: thermal energy storage comprising: a hot storage vessel for comprising a first phase change material that changes from a solid to a liquid at or above about 50°C; and a cold storage vessel comprising a second phase change material that changes from a liquid to a solid at or below about 0°C; a non-reversing electric heat pump that simultaneously heats the first phase change material in the hot storage vessel and cools the second phase change material in the cold storage vessel; and a building controller for controlling operation of the non-reversing electric heat pump, the building controller communicatively coupled to a communication network, wherein the building controller controls operation of the non-reversing electric heat pump based at least in part on an indication received over the communication network that electricity supply is generated from non-fossil fuel sources.

[0007] In accordance with the present disclosure there is further provided a building energy management system, comprising: a plurality of buildings connected to an electrical distribution grid, each building comprising: a hydronic heating/cooling system; a thermal storage system coupled to the hydronic heating/cooling system and providing hot and cold thermal storage; an electric heat pump linked to the hot and cold thermal storage of the thermal storage system; and a building controller operatively coupled to a communication network, the building controller configured to: estimate an amount of additional thermal energy that may be stored by the hot and cold thermal storage; estimate an additional amount of electrical power based on the electricity that would be consumed by the electric heat pump to supply the additional thermal energy; transmit an additional load capacity message over the communication network indicative of the additional amount of electrical power; subsequent to transmitting the additional load capacity message, receive a consumption increase message providing an indication to increase electricity consumption in the building; and operate the electric heat pump to consume at least a portion of the additional electrical power; and a central server operatively coupled to the communication network, the central server configured to: receive respective additional load capacity messages from one or more of the plurality of buildings; determine an aggregate amount of available load capacity based on the received additional load capacity messages; determine if electricity supply is currently generated from non-fossil fuels; and transmit to the one or more buildings respective consumption increase messages providing the indication to increase electricity consumption.

[0008] In accordance with the present disclosure there is further provided a building energy system, comprising: a hydronic heating/cooling system; a thermal storage system coupled to the hydronic heating/cooling system and providing hot and cold thermal storage; an electric heat pump linked to the hot and cold thermal storage of the thermal storage system; and a building controller operatively coupled to a communication network, the building controller configured to: estimate an amount of additional thermal energy that may be stored by the hot and cold thermal storage and a corresponding additional amount of electrical power that could be consumed by the electric heat pump to supply the additional thermal energy; transmit an additional load capacity message over the communication network indicative of the additional amount of electrical power that could be consumed; subsequent to transmitting the additional load capacity message, receive a consumption increase message providing an indication to increase electricity consumption in the building, the consumption increase message provided during a time when electricity is being generated from non-fossil-fuel sources; and operate the electric heat pump to consume the amount of additional electrical power.

[0009] In accordance with the present disclosure there is further provided a method of operating a heat pump in a building to reduce consumption of fossil fuels, the method performed by a building controller and comprising: estimating an amount of additional thermal energy that may be stored by hot and cold thermal storage in the building; estimating an additional amount of electrical power based on the electricity that would be consumed by an electric heat pump to supply the additional thermal energy; transmitting an additional load capacity message over a communication network indicative of the additional amount of electrical power; subsequent to transmitting the additional load capacity message, receiving a consumption increase message providing an indication to increase electricity consumption in the building; and operating the electric heat pump to consume at least a portion of the additional electrical power.

[0010] In accordance with the present disclosure there is further provided a fast response radiant hydronic heating/cooling system for a building, comprising: radiant hydronic panels disposed in any one of a floor, wall, or ceiling of a room in the building for radiating heat into or absorbing heat from the room; hydronic piping configured to carry a heat transfer liquid heated or cooled by a thermal energy storage system to an inlet of the radiant hydronic panels and carry the heat transfer liquid from an outlet of the radiant hydronic panels to an electric heat pump, the hydronic piping further comprising: a pump for pumping the heat transfer liquid through the hydronic piping; and a valve for controlling flow of the heat transfer liquid through the radiant hydronic panels; and wherein a building controller is configured to control opening and closing of the valve according to a predetermined fast response operation to provide a desired room temperature.

[0011] In accordance with the present disclosure there is further provided a method of determining if heating/cooling of a room in a building is required, comprising: receiving a setting of a desired room temperature including a background desired room temperature and an occupied desired room temperature; receiving sensor data indicating a current room temperature; receiving sensor data indicating whether the room is occupied; and determining if heating/cooling of the room is required by: if the room occupied, calculating a difference between the current room temperature and the occupied desired room temperature, wherein if the difference is greater than a first predefined threshold value, heating/cooling of the room is required; and if the room is unoccupied, calculating a difference between the current temperature and the background room temperature, wherein if the difference is greater than a second predefined threshold value, heating/cooling of the room is required.

[0012] In accordance with the present disclosure there is further provided a method of heating/cooling a room in a house that comprises a radiant hydronic heating/cooling system, comprising: receiving an instruction to perform a fast response operation for rapid heating/cooling of the room using the radiant hydronic heating/cooling system; and repeatedly opening and closing a valve that regulates a flow of a heat transfer liquid to radiant hydronic panels of the radiant heating/cooling system until a desired room temperature is reached, wherein the repeated opening and closing of the valve comprises: opening the valve for a first period of time to entirely displace a volume of the heat transfer liquid within the radiant hydronic panels; and closing the valve for a second period of time to promote radiant heat transfer with the volume of the heat transfer liquid within the hydronic radiant manifolds; wherein each time that the valve is closed, the second period of time increases in duration.

[0013] In accordance with the present disclosure there is further provided a displacement ventilation system for a building, comprising: ducting for receiving air from outside into the building at an inlet, transferring the air throughout the building, and exhausting air from the building at an outlet; a first gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing conducting a liquid desiccant, the first gas-liquid heat exchanger being disposed at the inlet of the ducting; and a second gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing fluidly coupled to the tubing of the first gas-liquid heat exchanger via a run-around piping loop and conducting the liquid desiccant, the second gas-liquid heat exchanger being disposed at the outlet of the ducting.

[0014] In accordance with the present disclosure there is further provided an enthalpy heat exchanger, comprising: a housing having an input and an output connected by a heat exchange section for conducting a heat exchange medium; and a length of small-diameter, vapour-permeable, liquid-tight tubing connecting a first port and a second port for conducting a liquid desiccant, the tubing in thermal contact with the heat exchange section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Further features and advantages of the present disclosure will become apparent from the following detailed description, taken in combination with the appended drawings, in which:

[0016] FIG. 1 shows a representation of a home energy system comprising a hydronic heating/cooling system;

[0017] FIGs. 2A and 2B show representations of a room controller;

[0018] FIG. 3 shows a method of heating using a radiant hydronic heating/cooling system;

[0019] FIG. 4 shows a graph representing a temperature of a room using radiant hydronic heating;

[0020] FIG. 5 shows a further graph representing a temperature of a room using radiant hydronic heating;

[0021] FIG. 6 shows a representation of a home energy system with integrated energy components;

[0022] FIGs. 7A and 7B respectively show a plan cross section and a vertical cross section of a gas/liquid heat exchanger;

[0023] FIG. 8 depicts a heat exchanger system with additional humidity control;

[0024] FIG. 9 depicts operation of the heat exchanger system described above with reference to FIG. 8;

[0025] FIG. 10 depicts a further operation of the heat exchanger system described above with reference to FIG. 8;

[0026] FIG. 11 depicts a building heating and cooling system incorporating additional liquid-to-liquid exchangers;

[0027] FIG. 12 depicts a heating and cooling system incorporating phase change storage; and

[0028] FIG. 13 shows a representation of a building energy system for a plurality of homes.

DETAILED DESCRIPTION

[0029] An energy efficient building is described that incorporates thermal storage in order to reduce the dependence upon electricity generated using fossil fuels. The building may use an electric heat pump to heat and cool hot and cold storage sections of the thermal storage. The thermal storage may store thermal energy from the electric heat pump during times when electricity is generated from clean sources and supply thermal energy during times when electricity is generated using fossil fuels. The thermal storage may be used in conjunction with a hydronic heating and cooling system to meet the heating and cooling demands of the building. Fast response heating and cooling techniques may be provided in order to quickly heat or cool a room or space in response to demands such as occupancy, which may reduce the heating/cooling demands of the building. The building system may further use a vapour-permeable tubing filled with a liquid desiccant within an enthalpy air exchanger in order to provide humidification and dehumidification of the building. As described further herein, the building may provide various heat sinks and sources that can use or supply thermal energy. By balancing the heat and cooling demands using the heat sinks and sources it is possible to meet the daily heating and cooling demands of a building using the thermal energy that was generated, and stored in the thermal storage, during periods when electricity is generated from clean sources.

[0030] FIG. 1 shows a representation of a building heating and cooling system comprising a fast response hydronic heating/cooling system. A residential building 102 is depicted schematically. It will be appreciated that the building may include multiple rooms, floors, windows, etc. that are not depicted in FIG. 1. Although FIG. 1 is described with reference to a residential building, a person skilled in the art will readily appreciate that the features of FIG. 1 may similarly be applied to other types of buildings such as office buildings, commercial buildings, recreational buildings, etc. An insulated building envelope encloses an interior space 104. The building envelope may be air-tight to reduce losses from uncontrolled air-flow. Although the building envelope is air-tight, the envelope will still include openings such as doors and windows, however these openings may be sealed, for example by doors or windows. Accordingly, the building envelope can be substantially sealed to provide an air-tight envelope. The building envelope, including exterior windows and doors sealing openings in the envelope, provides a high-R value insulation for the interior space which reduces the heating and cooling demands. The building 102 uses hydronic panels 106 to heat and cool the interior space 104. It will be appreciated that multiple hydronic panels may be provided to heat and cool multiple rooms, spaces or areas. While the hydronic panel 106 is depicted as being located in a ceiling, hydronic panels may additionally or alternatively be disposed in walls and/or floors. The hydronic panel 106 may be supplied with a heat transfer liquid to either heat or cool the panel and so the interior space 104. The heat transfer liquid may be heated or cooled in various ways. A thermal storage component 112 may provide both a hot storage section and a cold storage section, which can provide thermal energy for heating and cooling the heat transfer fluid. The thermal storage component 112 may combine the hot and cold storage sections together, for example in a stratified storage tank. Alternatively, the hot storage section may be separate from the cold storage section. An electric heat pump 114 is controlled to both heat the hot storage section and cool the cold storage section. The electric heat pump 114 may be a two-sided heat pump that extracts energy from the cold storage, further cooling the cold storage, and supplies the extracted energy to further heat the hot storage.

[0031] The thermal storage may be used to heat or cool a heat transfer liquid that is delivered to the hydronic radiant panel 106 by means of a piped distribution system 108 which may include valves, manifolds, pumps 110 etc. A building controller 116 controls the operation of the heat pump 114, the thermal storage 112, and the piped distribution system 108, to control the overall operation of the heating and cooling system and provide fast response heating and cooling functionality 118. The building controller 116 may also be linked to other components of the home energy system, either by a wired or wireless communication link.

The building controller 116 may also be communicatively coupled to the Internet as well as to the power distribution grid, for example via a smart meter, and may be configured to communicate with a central server to coordinate consumption of electrical power generated by non-fossil fuels, as will be described in more detail further below. The controller 116 can control the flow of the heat transfer liquid to the hydronic panel 106 to control the heating/cooling of the space.

[0032] When multiple hydronic panels are present, they may be controlled individually or in groups depending upon the configuration of the piped distribution system 108. The controller 116 may control the flow of the heat transfer liquid to the hydronic panel using fast response heating/cooling functionality 118. The fast response heating cooling functionality 118 causes pulsing of the heat transfer liquid to the hydronic panel. The pulsing of the heat transfer liquid allows the hydronic panel to be filled with the heat transfer liquid, and then conduct to the panel surface before another pulse of the heat transfer liquid is supplied. The fast response heating and cooling functionality 118 allows hotter or colder heat transfer fluid to be used, which may provide a quicker response to heating and cooling demands. That is, the fast response functionality may allow a space to more quickly reach a desired temperature, which can provide greater energy efficiency by increasing temperature setbacks since the desired temperature can be more quickly reached once required. For example, in a home, the setback temperature may be reduced such that an unoccupied room is allowed to cool further since the room may be quickly heated to a comfortable temperature once occupancy is detected.

[0033] To provide the same energy-saving advantages of temperature setbacks in multiple rooms or zones, the building controller 116 may be configured to perform fast response heating and cooling functionality 118 within each of the different rooms or zones that can be individually controlled. Instead of using single thermostat or controller for the building, the building controller 116 may be communicatively coupled with a series of room thermostat sensor/controllers 120. The room controllers 120 may be linked to the main building controller 116 by a communication interface such as Wi-Fi™, for example. When the room is occupied (e.g. if an occupant is detected for a predetermined period of time), the room thermostats/controllers 120 can transmit a request to the building controller 116 to implement the fast response heating/cooling functionality to rapidly adjust the temperature of the room from the setback temperature to the desired temperature. Additionally and/or alternatively, the room thermostats/controllers 120 may transmit the request to rapidly adjust the temperature when requested by the occupant, for example using voice-activated controls or touch inputs. During periods of heating demand, such as during winter, the setback temperature may be set lower than the desired occupancy temperature while during periods of cooling demand, such as during summer, the setback temperature may be set higher than the desired occupancy temperature. The setback limits may be based on acceptable response time to reach desired thermal conditions. Since the fast response heating cooling allows the temperature to be quickly adjusted, the setback temperatures may be set higher or lower while still provide an acceptable response time to reach the desired occupancy temperature. The higher or lower setback temperature, depending upon whether there is a cooling or heating demand, results in less cooling or heating of unoccupied rooms and as such reduces the energy consumption.

[0034] As described in more detail with reference to FIGs. 3 to 5, to achieve the required fast temperature response a pulse operation may be employed where fluid at a higher / lower temperature than is typically used for hydronic heating /cooling is supplied to the radiant hydronic ceiling panels 106. Each pulse delivers sufficient fluid to fill the panels and the fluid remains in the panels while it is allowed to cool-down / warm-up before another pulse of hot / cold fluid is supplied to the panels 106.

[0035] Compared to conventional forced air systems particularly for buildings with high-R envelopes, radiant heating / cooling systems offer a number of key advantages. The radiant heating/cooling system as described herein may reduce the heat transfer rate through the building envelop and via ventilation air and so reduce the heating and cooling loads. The interior space 104 can be maintained at a lower or higher temperature while still maintaining the same comfort conditions for the room occupants as a result of the radiant heating / cooling. The heating/cooling load may be further reduced by using a low emissivity coatings on windows and low emissivity paint on interior surfaces that are not radiant heating sources such as the hydronic panels. The low emissivity paint and coating help to further reduce temperature differences with the outside air since the mean radiant temperature is improved by reflecting radiant panel output. In addition, radiant ceiling heating / cooling system using the fast response heating/cooling functionality may have a faster response time than conventional forced air systems. To control the pulse operation of the fast response heating / cooling functionality 118, the room controller 120 may incorporate two separate temperature sensors that measure air and mean radiant temperatures respectively, as further described with reference to FIGs. 2A and 2B. By averaging these two measurements the operative temperature of the room can be determined. The operative temperature better approximates the occupants' experience of thermal comfort.

[0036] FIGs. 2A and 2B show representations of a room controller. FIG 2A shows a three-dimensional view and FIG 2B shows a cross section of a room controller 200 that controls the operation of the fast response radiant heating / cooling ceiling panels. The room controller 200 may be used as room thermostats/controllers 120 described with reference to FIG. 1. The room controller 200 may also be referred to herein as a radiant sensor thermostat or an operative temperature sensor. When multiple room controllers are present in a building, one of the room controllers may additionally function as a building controller.

[0037] The room controller 200 incorporates two sensors 210, 206 that separately measure the radiant and air temperatures. Based on these two sensor measurements, the room controller calculates the effective operative temperature with this criterion used in controlling the delivery of heating or cooling of the space.

[0038] The radiant sensor 210 may be located on radiant sensing panel 208 that is sloped and oriented in the direction of the radiant ceiling panels (i.e. a plane defined by the radiant sensing panel 208 has a normal that intersects a plane defined by the radiant hydronic panels in the ceiling of the room). The front face of the sloped radiant sensing panel 208 incorporates a selective surface 212 which minimizes both the radiant heat transfer back to the interior space 104 and also mimics the spectral absorptivity and the spectral emissivity of a human in the same environment. An insulating housing 202 blocks the radiant sensor 210 from any heating effects from a microprocessor 204 and also from any room air heating / cooling convective effects. The air temperature sensor 206 is placed within an insulated housing 202 so that it only measures the base room temperature and is shielded from any radiant heat transfer effects.

[0039] A microprocessor 204 converts the two sensor measurements to data that can be communicated to a home controller (such as building controller 116 described with reference to FIG. 1). The microprocessor 204 can also perform logical operations on the sensor readings and operate as a thermostat to signal the need for additional heating / cooling.

[0040] As well as the two temperature sensors 210, 206 and microprocessor 204, the room controller 200 may also comprise a humidity sensor (not shown) that can be combined with the air temperature sensor. The humidity sensor allows the impact of humidity on human comfort to be assessed and by a link to the dehumidifier ensures that room temperatures are within the comfort zone as recommended in standard psychometric charts. In addition to humidity, the room controller 200 can incorporate, or at least be in communication with, a series of additional sensors that measure various criteria, including: occupancy, air quality, interior light levels, etc. The room controller 200 can also incorporate a number of other additional features, including: wireless communication radios, wired communication interfaces, occupancy sensors, a microphone, a speaker, and a touch display screen.

[0041] In addition to sensing the operative temperature, the room controller may provide an interface for interacting with the heating and control system. For example, the room controller may have a touch screen for controlling parameters such as a desired occupancy temperature. Additionally or alternatively, the room controller may provide a voice controlled interface that allows a user to speak commands to the room controller. The processing of the commands may be performed on the room controller, or on other devices including on a remote server. The spoken commands may control the heating and cooling system as well as possibly controlling other systems or functionality. For example, the room controller may provide voice assistant functionality that may be provided by one or more third parties.

[0042] FIG. 3 shows a method of heating using a radiant hydronic heating/cooling system. The flow chart 300 depicts a control method that may represent a subroutine providing the fast response heating and cooling functionality 118 in the application software of the building controller 116 that controls the fluid flow / pulses to the hydronic heating/cooling panels 106 as described with reference to FIG. 1. The method 300 is depicted with particular regard to heating a room. It will be readily apparent that a similar method may be applied for cooling a room.

[0043] The building controller initiates fast response heating (302) by charging the fast-response heating/cooling panels with fluid. The effective operative room temperature is calculated based on sensor measurements of air and mean radiant temperature measurements and a determination is made if the current temperature is less than the occupants' desired room temperature (304). If the answer is "No", the method returns to the room control software (312). If the answer is "Yes", the method determines a pulse rate (306). The pulse rate may be determined based on various parameters that are either measured or pre-set in the controller's software. For example, the pulse width may be predetermined, and pre-set, in the controller or may be determined dynamically. The various parameters used in dynamically determining a pulse width may include: the thermal mass of the hydronic panels, the volume of liquid contained in the panels; the flow-rate of the pumped fluid; the heat transfer coefficients; the rate of heat transfer from the radiant ceiling panels to the occupants or surrounding room surfaces, etc. Once the pulse rate is determined, electrically actuated valve(s) and/or power pump(s) are opened (308) in order to fill the hydronic heating/cooling panels with a fresh charge.

[0044] When a predetermined quantity of fluid has filled the hydronic heating cooling panels, the valve(s) or pump(s) are closed or shut off (310). If the flow-rates are known or measured, and if the volume to fill the panels is also known, the closing or shutting-off of the valve(s) or pump(s) (310) may involve using a timed duration calculated in the determination of the pulse rate. Additionally and/or alternatively a temperature sensor located on the piped exit from the ceiling panels may be used to detect an appropriate change in fluid temperature. The method 300 returns 300 to the determination at 304, thereby continuing until the current room temperature reaches the desired room temperature.

[0045] FIG. 4 shows a graph representing a temperature of a room using radiant hydronic heating. Particularly, the graph 400 shows the impact of the pulsed supply of heated fluid to hydronic heating/cooling panels 106 on various measured temperatures within a room when a fast response radiant heating operation is performed. The vertical axis 402 of the graph represents temperatures measured in degrees centigrade and the horizontal axis 404 represents time duration in minutes.

[0046] The top solid line 406 represents the control signal for pulse operation of the hydronic radiant ceiling as a series of ON/OFF or High/Low values. The second solid line 408 represents the measured surface temperature of the radiant ceiling panels. The single dash line 410 represents the set point or targeted effective operative temperature within the room.

The single dash / double dot line 412 represents the effective operative room temperature which is indicative of the occupant's thermal comfort level. The triple dash / double dot line 414 represents the air temperature within the interior space.

[0047] The operative temperature is based on measurements of radiant room air temperature (Ta) and mean radiant temperature (MRT) and is calculated by (Ta + MRT)/2. The operative temperature may be calculated using the sensor data from the room controller. The building controller 116 as shown in FIG. 1, controls the flow of fluid in both duration of pulses and timing between pulses so that the targeted effective operative temperature can be quickly reached. As depicted in FIG. 4, the control pulses 406 may have a constant width. As shown in the graph 400, the radiant temperature of the ceiling increases quite rapidly while the air temperature only edges up slowly. As a result, the effective operative temperature is achieved in a matter of minutes. Once the desired operative temperature has been reached, the pulsing of the hydronic panels may be stopped, or the pulse duration and frequency adjusted to maintain the desired operative temperature.

[0048] The graph depicted in FIG. 4 assumes that the radiant panels have low mass. If the heating panels have a relatively large thermal mass, heating control pulses depicted in FIG. 4 may result in significant overshoot of the operative temperature. The overshoot may be mitigated by varying the pulse width and frequency as the rooms operative temperature approaches the desired temperature.

[0049] FIG. 5 shows a graph representing a temperature of a room using radiant hydronic heating having a relatively large thermal mass. As depicted, as the room's operative temperature 512 gets closer to the desired comfort temperature510, there is may be a longer time lapse between the control pulses 506 with the timing between pulses set to enable sufficient time for the fluid and the panel surface 508, to approach the room temperature by a predetermined amount. Increasing the time between pulses as the room's operative temperature approaches the desired room temperature also helps to prevent overshoot of the desired room temperature. In order to further prevent overshoot or oscillations, the control system may implement a more complex algorithm that switches on-and-off the pulses using PID (such as Pulse Width Modulation) methods. Regardless of the particular control system, the control signal will still appear as a series of on-and-off states.

[0050] FIG. 6 shows a representation of a home energy system with integrated energy components. More particularly, FIG. 6 shows a schematic cross section of a residential building 602 incorporating a fast response heating and cooling system as previously described in FIG. 1 as well as several other energy components / sub-systems that may be retrofitted in existing buildings, or incorporated in new builds, and that further help to improve the energy efficiency of the building and reduce reliance on electricity generated using fossil fuels.

[0051] Similar to FIG. 1, in FIG. 6 an insulated building envelope encloses an interior space 604 which is heated by hydronic radiant ceiling heating and cooling panels 606. A two-sided electric heat pump 614 can supply both hot and cold thermal energy which may be stored in a thermal storage 612. Since both the heat and cold from both sides of the heat pump can be usefully utilized in the energy efficient building heating/cooling system, there is inherently a 100% improvement in heat pump efficiency compared to a heat pump which produces either heat or cold as waste due to cooling or heating respectively. Further, a single heat-pump can deliver space heating, air conditioning and domestic hot water heating. Further, excess cold liquid can be used to efficiently collect low-grade heat / cold including ground heat, grey water, and passive solar. The thermal storage 612 is able to provide both hot and cold storage, either in a single stratified tank or in separate hot and cold tanks. The hot storage may be at a temperature, for example, at or above about 50°C, and the cold storage may be at a temperature, for example, at or below about 0°C. The thermal storage may be provided in various ways, including for example a stratified water tank that uses a single water tank to store both hot and cold water, in separate hot and cold water tanks or in separate tanks that use different materials as the thermal mass. Rather than using water for the hot and cold storage, other materials may be used. For example, the hot and cold storage may use respective phase change materials such as water/ice for the cold storage and paraffin wax for the hot storage. Advantageously, the hot storage vessel may be a shipping container used for shipping or otherwise transporting the paraffin wax. A heat exchanger may be pre-installed within the shipping container prior to filling with the paraffin wax. The cold storage vessel may be provided with hollow balls, which may be made from metal, that are filled with water. Regardless of how the thermal energy is stored, the thermal storage 612 can produce both hot and cold liquids that can be delivered to the hydronic ceiling panels 606 by means of a piped distribution system 608. The piped distribution system may comprise various tubing, valves, manifolds, pumps 610, etc. that allow hot and/or cold heat transfer fluid to be distributed from the thermal storage 612 to the desired hydronic panel 606. A central building controller 616 controls the operation of the heating and cooling system including the heat pump 614, the piped distribution system 608 and pumps 610, and so the radiant hydronic panels 606.

[0052] As further depicted in FIG. 6, a hydronic ground loop 624 comprising appropriate valves and/or pumps 626 is buried in the ground 622 and provides a source of geothermal energy which may be upgraded by the heat pump 614 to provide heating in the winter as well as providing an energy sink for cooling in the summer. The ground loop 624 provides a relatively large sink and source for thermal energy which may be used to balance the heating and cooling loads of the building. The ground loop may be buried, for example, at least about 25 mm below the frost line.

[0053] The residential building 602 may also incorporate a displacement ventilation system 628 and a run-around heat exchanger 630. In the displacement ventilation system, outside air is received through a supply duct 632 which may be at the basement level and polluted air is exhausted from the building through an exhaust duct 634, which may be at the roof level. Both the basement supply duct 632 and the roof exhaust duct 634 incorporate a gas/liquid heat exchanger 618a, 618b that can precondition incoming supply air as well as extract thermal energy from the exhaust air. The two gas/liquid heat exchangers 618a, 618b are connected by piping 620 to form a continuous loop through which a liquid desiccant may be circulated in order to control humidity levels. The supply heat exchanger 618a provided in the supply duct 632 receives incoming ventilation air 638a from outside and supplies ventilation air 640a to the interior of the building for the displacement ventilation system 628. The exhaust heat exchanger 618b provided in the exhaust duct 634 receives ventilation air 638b from the displacement ventilation system 628 of the building 602 and exhausts the out-going ventilation air 640b to outside of the building 602.

[0054] As described in more detail with respect to FIGs. 7A, 7B, the gas/liquid heat exchangers 618a, 618b may be fabricated from small diameter, vapour permeable plastic piping and the fluid used in the gas/liquid heat exchanger may be a liquid desiccant that can extract or supply moisture from or to the air. The liquid desiccant used in the gas/liquid heat exchanger can be circulated between the two gas/liquid heat exchangers 618a, 618b through the piping 620. Accordingly, in the summer the run-around heat exchanger 630 may precool and dehumidify the incoming supply air 638a using the liquid desiccant. The exhaust heat exchanger 618b exhausts the outgoing humid ventilation air 640b including the absorbed moisture from the liquid desiccant which is removed by heating of the liquid desiccant by the exchanger 618b. In the winter, the run-around heat exchanger 630, and in particular the exhaust exchanger 618b, recovers heat and moisture from the out-going ventilation air 640b at the roof level and preheats and humidifies incoming ventilation supply air 638a at the supply heat exchanger 618a. The displacement ventilation system 628 comprising the run-around heat exchanger 630 may further help to reduce electricity demands of the building 602.

[0055] Although the heat exchangers 618a, 618b are depicted as heating/cooling the liquid desiccant using incoming supply air or outgoing exhaust air, it will be appreciated that other sources may be used to heat or cool the liquid desiccant. For example, various sources including solar thermal, heat pump, hot or cold heat transfer fluid from the thermal storage 612, or other sources of heat can be used to heat or cool the liquid desiccant. By heating or cooling the liquid desiccant, moisture can be extracted from or absorbed by the liquid desiccant, and so control humidity levels in the building. The heat exchangers 618a, 618b may be considered as enthalpy exchangers that can transfer both heat and vapour from air to a liquid desiccant and vice versa.

[0056] FIGs. 7A and 7B respectively show a plan cross section and a vertical cross section of an example gas/liquid heat exchanger 700. The gas/liquid heat exchanger 700 may be used as the gas/liquid heat exchangers 618a, 618b in the run-around heat exchanger 630 as described with reference to FIG. 6.

[0057] The gas/liquid heat exchanger 700 comprises an outer enclosure 702 and an inner in-take core 704. A series of small diameter plastic pipes 706 are separated and spirally wrapped around the inner core 704 which is typically fabricated from a perforated metal sheet that distributes the air evenly. The spiral assembly results in multi-row tubing in essentially counter flow configuration with the air and with the number of coils determining the temperature of the incoming or outgoing air from the building.

[0058] Between the outer housing 702 and the inner spiral piping assembly 706, a perimeter out-take space 716 is formed. The small diameter plastic piping 706 is connected to inner and outer tubular manifolds 708a and 708b that are in turn connected to the supply and return piping of the run-around heat exchanger (not shown).

[0059] A top plate 712 prevents the air from exiting the gas/liquid heat exchanger above of the inner core 704 and a bottom plate 710 prevents air from entering into the gas liquid heat exchanger between the outer enclosure 702 and the inner core 704. Incoming air ducts are connected to the inner in-take opening 714 and outgoing air ducts are connected to the perimeter out-take opening 716.

[0060] Compared to conventional fan coil heat exchangers, the efficiency of the small diameter, spiral-pipe heat exchanger is higher as the small diameter piping provides for increased surface area and air can meander between the small diameter pipes. The heat exchanger 700 can be used for sensible heat recovery where there is a need to supply heated ventilation air such applications

[0061] The small diameter piping 706, which may have a diameter of about 3mm, although larger diameters may be used, may be made from permeable plastic material and for the heat transfer fluid to be a liquid desiccant. As most liquid desiccant materials are highly corrosive, one embodiment is to fabricate the plastic tubing as a plastic co-extrusion with a corrosion resistant but permeable fluorocarbon material such as Teflon™ on the pipe interior and a hygroscopic material such as nylon on the pipe exterior. Alternatively, the vapour permeable small diameter piping may be made as an extrusion of material that is not susceptible to corrosion by the liquid desiccant. For example a vapour permeable material such as PEBAX™ 1274, which is a thermoplastic elastomer made of hydrophilic flexible polyether and rigid polyamide may be used to fabricate the piping. Suitable materials for use in manufacturing the small diameter vapour permeable, fluid tight, piping that are not corroded by a selected liquid desiccant will be apparent to one of ordinary skill in the art.

[0062] As depicted in FIGs. 7A, 7B the liquid/gaseous enthalpy exchanger may comprise multiple small diameter vapor-permeable, liquid-tight tubing such as 3 mm polyether-B-amide with tangential or longitudinal gas flow that is arranged for liquid counter flow either between rows or along the length of the tubing. In contrast to enthalpy exchangers that use flat membranes, the use of the vapour permeable tubing allows the liquid desiccant to be circulated in a closed loop with hydrostatic pressure, is more readily fabricated, and avoids leakage or airborne contamination. The enthalpy exchanger may use a spiral-wound set of tubes manifolded at each end such that gas flows tangentially between an inner cavity and an outer cavity counter flow to the liquid flow in the tubes.

[0063] While the exchanger depicted in FIGs 7A, 7B is shown as a cylindrical exchanger, different shapes and configurations are possible.

[0064] FIG. 8 depicts a heat exchanger system with additional heating/cooling and humidity control. The heat exchanger system 800 may be used as the run-around loop exchanger 630 described above. The heat exchanger system 800 comprises a first air-to-liquid enthalpy exchanger 802 that is fluidly coupled to a second air-to-liquid enthalpy exchanger 804. The two exchangers 802, 804 may be connected by piping 806a, 806b that carries a liquid desiccant that can be circulated by one or more pumps 808. As outside supply air 810a enters it is preconditioned by the first exchanger 802 and is supplied to the building as preconditioned supply air 810b. As building air 812a is exhausted, the enthalpy exchanger can extract moisture and heat from the air, or extract heat and moisture from the liquid desiccant into the air 812b to be exhausted out of the building. Liquid-to-liquid heat exchangers 814, 816 may be provided to heat and or cool the liquid desiccant as it flows between the air-to-liquid enthalpy exchangers 802, 804. Each of the heat exchangers 814, 816 may have a respective pump 818, 824 for pumping a heat transfer fluid 820, 826. The heat transfer fluid 820, 826 supplied to either of the heat exchangers 814, 816 may be either heated or cooled. By heating or cooling the liquid desiccant, greater control over the temperature and humidity of the incoming supply air and outgoing exhaust air can be provided. For example, by cooling the liquid desiccant at heat exchanger 814, the incoming supply air 810a will be further cooled and more moisture absorbed from the incoming supply air into the liquid desiccant. Similarly, by heating the liquid desiccant at heat exchanger 816, excess moisture absorbed into the liquid desiccant will be expelled into the outgoing exhaust air 812b. The reverse process, namely heating the liquid desiccant at heat exchanger 814 and cooling the liquid desiccant at heat exchanger 816 may be used to further preheat and humidify incoming supply air 810a, while extracting heat and moisture from the exhaust air 812a before it is exhausted to the outside 812b. By supplying hot or cold fluid to the heat exchangers 814, 816, the temperature and humidity levels of the supply air exiting the enthalpy exchanger 802 and exhaust air exiting the enthalpy exchanger 804 may be more precisely controlled. When the liquid desiccant is used to raise the humidity of the building, the concentration of the liquid desiccant may increase, and as such a water fill tank 830 may be provided to top-up the liquid desiccant. While the fill tank 830 is depicted as being located at a top of the building, it is possible to provide the fill tank 830 at other locations, although if provided at a lower point in the loop, the fill tank would need to be sealed to prevent the liquid desiccant from emptying above the fill tank.

[0065] FIG. 9 depicts the operation of the heat exchanger system described above with reference to FIG. 8. The operation 900 depicted in FIG. 9 assumes that there is a heating load such as would occur during the winter. Accordingly the supply air 810a is cold dry air which is pre-heated and humidified by the supply enthalpy exchanger 802 which is supplied with hot liquid desiccant having a high moisture content as depicted at point 902 and as such will both heat the incoming air as well as supply the dry air with moisture. The liquid desiccant leaving the supply enthalpy exchanger 802 will have been cooled and lost moisture and as such is depicted at point 904 as being warm (as opposed to hot) with a low moisture content. The liquid desiccant may then be cooled at the liquid to liquid heat exchanger 816 and so the liquid desiccant at point 906 will be cold with a low moisture content. The air to be exhausted will have been further heated and as such is depicted as being hot wet air. As the hot wet air is exhausted through the air-liquid enthalpy exchanger 804, the cold liquid desiccant will extract heat from the air as well as moisture and as such the exhausted air will be warm (as opposed to hot) and dry. The liquid desiccant leaving the exhaust enthalpy exchanger 804 at point 908 will be warm with a high moisture content. The warm liquid desiccant may then be further heated by the liquid-to-liquid exchanger 814 to provide the hot liquid desiccant with high moisture at point 902, which can again be used to heat and humidify the cold dry supply air.

[0066] FIG. 10 depicts the operation of the heat exchanger system described above with reference to FIG. 8. The operation 1000 depicted in FIG. 10 assumes that there is a cooling load such as would occur during the summer. Accordingly the supply air 810a is hot wet air which is pre-cooled and dehumidified by the supply enthalpy exchanger 802 which is supplied with cold liquid desiccant having a low moisture content as depicted at point 1002 and as such will both cool the incoming air as well as absorb the moisture from the humid incoming air. The liquid desiccant leaving the supply enthalpy exchanger 802 will have been warmed and gained moisture and as such is depicted at point 1004 as being warm with a high moisture content. The liquid desiccant may then be further heated at the liquid to liquid heat exchanger 816 and so the liquid desiccant at point 1006 will be hot with a high moisture content. As the cool dry conditioned air is exhausted through the air-liquid enthalpy exchanger 804, the hot liquid desiccant will heat the exhaust air as well expel the absorbed from the liquid desiccant into the exhausted air so it will be warm and wet. The liquid desiccant leaving the exhaust enthalpy exchanger at point 908 will be warm with a low moisture content. The warm liquid desiccant may then be further cooled by the liquid-to-liquid exchanger 814 to provide the cold liquid desiccant with low moisture at point 102, which can again be used to cool and dehumidify the hot and humid supply air.

[0067] FIG. 11 depicts a building heating and cooling system incorporating additional liquid-to-liquid exchangers. The building 1100 is similar to those depicted above, however certain components have been omitted or simplified for clarity. The building 1100 uses two additional liquid-to-liquid heat exchangers, in conjunction with the two air-to-liquid enthalpy exchangers 1102, 1104. In FIG. 11, it is assumed that there is a cooling load, for example as would be the case in the summer, and as such additional cooling and dehumidifying of incoming supply air is desirable. The first air-liquid exchanger 1102 preconditions the incoming supply air 1108 which cools and dehumidifies the supply air. The liquid desiccant may absorb some of the excess moisture 1110 from the supply air. While the air –liquid enthalpy exchanger 1102 cools and dehumidifies the incoming air, it may not be sufficient. Accordingly a first liquid-to-liquid exchanger 1112a may be provided which may be supplied with cold water (not shown) to further cool the liquid desiccant before the first enthalpy exchanger 1102 and provides additional cooling and dehumidification of the incoming air. After exiting the first enthalpy exchanger, the liquid desiccant may be heated by supplying a second heat exchanger with hot fluid. The heated liquid desiccant will expel the absorbed moisture from the supply air into the exhaust air at the second enthalpy exchanger 1304.

[0068] In addition to the liquid-to-liquid exchangers 1112a, 1112b the building may also supply liquid desiccant to a second liquid-to-liquid exchanger 1120, which may be used as the hydronic panel. The hydronic panel 1120 may comprise tubing for circulating the heat transfer fluid for heating or cooling the panel as well as vapour permeable small diameter tubing for circulating the liquid desiccant through the panel. The heat transfer fluid may be supplied with cold water pumped from the cold supply 1116 by a pump 1122. The cold water may cool the radiant hydronic panel and so the room. Additionally, liquid desiccant may be pumped through the liquid-to-liquid exchanger 1120 by pump 1124, which will also be cooled by the water and as such will absorb further moisture.

[0069] In addition to controlling the humidity of the room, using a liquid-to-liquid exchanger with vapour permeable piping circulating the liquid desiccant as the radiant panel allows quicker cooling to be provided, or a smaller panel used for the same cooling performance. The cooling performance of a radiant panel depends upon the temperature of the cooling fluid, and the colder the fluid the higher the cooling performance. However, if the cooling fluid is too cold, condensation will form on the radiant panel, which is undesirable. By including the liquid desiccant within the vapour permeable piping of the liquid-to-liquid exchanger radiant panel, the excess moisture which would otherwise condense can be absorbed into the cooled liquid desiccant. Accordingly, the cooling fluid supplied to the liquid-to-liquid exchanger radiant panel may be colder without causing condensation.

[0070] As described above, exchangers may use small diameter vapour permeable, liquid tight, piping to circulate a liquid desiccant that can be used to improve the heating/cooling and humidity control within a building. The vapour permeable tubing may be used in both liquid-to-air exchangers as well as liquid-to-liquid exchangers. The heating/cooling and humidity control provided by the liquid desiccant in an air-to-liquid exchanger is passive, that is it is dependent upon the temperature of the passing air, which may not be directly controlled, the liquid-to-liquid exchangers can provide control of the heating / cooling and humidity control by supplying hot or cold water or other fluids.

[0071] As described above hydronic radiant panel heating and cooling using vapour permeable tubing thermally connected to or imbedded in a material that permits moisture transfer may be used to extract or supply moisture to adjacent air in a space being conditioned. The fluid may be water, a freeze-protected aqueous solution, or a liquid desiccant solution. The radiant panel with the liquid desiccant in vapour permeable piping allows the space humidity, temperature, and radiant environment to be regulated by controlling the fluid temperature or desiccant concentration. Further, fluid and panel surface temperatures below the condensing temperature of the conditioned space air can avoid condensation formation on or within the panel. A radiant panel with a liquid-to-liquid exchanger may have the tubing embedded in a material that forms a drywall panel which is permeable to moisture. Similarly, the tubing may be installed and covered with vapour-permeable plaster. Further, it is possible to thermally bond the tubing to a conductive material that is perforated. It will be appreciated that above exchangers utilizing a vapour permeable small diameter piping to circulate a liquid desiccant may be used in other configurations and applications than those described.

[0072] The above has described a building system that can meet heating and cooling demands as well as humidity control while consuming little electricity. Further, a significant portion of the electricity consumed may be used to heat and cool a thermal storage system, which allows the electricity to be consumed during periods that the electricity is generated by clean sources.

[0073] FIG. 12 depicts a heating and cooling system incorporating phase change storage. The system 1200 uses a two-sided heat pump 1202 to simultaneously provide heat to a hot storage section 1204 and cool a cold storage section 1206. The non-reversing heat pump 1202 simultaneously stores thermal energy for heating and cooling in the storage vessels 1204, 1206 using phase change materials. The cold storage 1206 may contain water which is converted to ice as heat is extracted by the heat pump 1202 and the hot storage may contain a phase change material that transitions above 50 C such as paraffin wax as heat is added by the heat pump 1202. The hot storage vessel may be a shipping container used for shipping or otherwise transporting the paraffin wax. A heat exchanger may be pre-installed within the shipping container prior to filling with the paraffin wax. The cold storage vessel may be provided with hollow balls, which may be made from metal, that are filled with water.

[0074] The system may comprise various pumps 1208, 1212 and valves 1210, 1214 for circulating hot and cold fluids as required. This system enables heat pump operation to be scheduled to reduce electricity peak demand, minimize GHG emissions when fossil fuel generation is being dispatched, and reduce electricity costs. The thermal energy stored in the hot and cold storage sections can be supplied, via one or more valves or manifolds 1216 to heating or cooling loads as required. The heating and cooling loads may be supplied with a 4-pipe hydronic distribution system, comprising a hot supply pipe, hot return pipe, cold supply pipe and cold return pipe, capable of simultaneous heating and cooling directly from the cold and hot storage tanks, or the loads may be supplied with a 2-pipe hydronic distribution system capable of supplying either a hot supply and return or a cold supply and return. The heat transfer fluid, whether hot or cold, may be pumped to the respective loads by various pumps 1218a, 1218b, 1218c. The loads are depicted as being radiant panels 1220a, 1220b, 1220c, for different rooms. Although multiple radiant panels are depicted, only a single manifold 1216 is depicted although each radiant panel, or load may be associated with a respective manifold. Each manifold may be for example a motorized 6 port valve that has a hot supply port, a hot return port, a cold supply port, a cold return port, a load supply port and a load return port. The valve may be electronically controlled to supply either hot or cold fluid to the load. Each room may have an associated room controller 1222a, 1222b, 1222c that may, for example be used to measure the operative temperature of the room, as well as other parameters such as humidity and communicate the information to a central building controller 1224 that can control the operation of the various components to provide the required, or desired heating/cooling. The room controllers may provide a voice-activated interface that allows the temperature of the room, or possibly other rooms or zones, to be adjusted. Further, the building or room controllers may determine if a room is unoccupied for a period of time, or is likely to be unoccupied in the future, and can adjust the setback temperatures accordingly. The central building controller 1224 may be communicatively coupled via a network 1226 to a remote server 1228 that can provide smart building control functionality 1230 to the controller. The smart building control functionality may provide various functionality including, for example remote access to the controller. Further, the central server 1228 may allow the smart building control functionality 1230 to provide an indication to the controller 1224 when to operate the heat pump based on the availability of electricity produced from clean sources.

[0075] In winter when the heating load is high, the heat pump may not be able to extract further heat from the water in the cold storage if the cold storage is solid ice and as such the cold storage may be provided with heat from, for example, geoexchange 1228 wastewater heat, heat from radiant cooling of rooms or other sources of waste heat in order to prevent the storage from freezing. The ground loop may be provided, for example, as a loop of plastic tubing located around the perimeter of the building and buried at least about 25 mm below the frost line. In order to prevent the ground surrounding the ground loop from becoming over heated or over cooled the loop may be operated intermittently to allow the ground surrounding the piping to re-cool or re-heat. Additional heat to cold storage can be added by space cooling of overheated rooms which may be overheated due to such factors as solar gains or wood heating. Domestic water heating 1232 may extract heat from the hot water storage to heat the water. During the cooling season the heat pump extracts heat from the cold storage which receives heat when providing space cooling and dehumidification. As described above, a liquid desiccant may be heated and/or cooled in order to provide additional pre-heating/cooling and humidification/dehumidification of incoming air. The heating and cooling of the liquid desiccant can be provided from the hot and cold storage. The phase change storage in co-operation with the two-sided heat pump can provide sufficient thermal energy to meet the heating and cooling loads of a building using the systems described above.

[0076] A single energy efficient building is described above that can meet its heating and cooling demands using electricity consumed during periods when only clean energy is being produced. When there are multiple energy efficient buildings, it is possible to coordinate the operation of the buildings to provide additional features. Since the building controller may be network connected, the smart building control 1230 described above may be augmented to coordinate the operation of multiple buildings. As described further below, the controllers may provide an estimate of additional electrical load that they could consume and the central server may aggregate the possible additional load and coordinate delivery and consumption of electricity at a time when the electricity is produced from clean sources.

[0077] Because of climate change, there is global recognition that there is a need to radically reduce the use of fossil fuels by a 2050 deadline and it is increasingly recognized that for low grade applications such as space heating and cooling the use of fossil fuels needs to be fully eliminated and existing buildings need to be retrofitted. The present disclosure is applicable to new buildings as well as to retrofitting buildings towards providing zero-emission (ZE) performance, and further describes how building equipment and sub-systems can interface with an electricity grid/distributor to better match supply of electricity that is generated from non-fossil fuel sources with electricity consumers.

[0078] Typically, homes or buildings incorporate a thermostat that can be programmed for temperature setbacks when the building is unoccupied or when people are in bed sleeping. With a well-insulated and electrically heated building, the problem with conventional programmable thermostats is that during the night setback period, the interior thermal mass gradually cools down and no use is made of the excess off-peak clean renewable power that is typically available from the utility grid during the night. In the morning when the room temperature is turned-up, the cooled down thermal mass is then heated up using peak power that in the case of many utilities is generated using fossil fuels. Although described with regard to heating demands, a similar process occurs for cooling demands. As a result, conventional programmable thermostats increase, and not decrease, GHG emissions.

[0079] Furthermore, in existing electricity distribution networks it is difficult for a grid control authority to exactly match power demand with power supply and so particularly in off-peak periods, it is often necessary to export power to neighboring utility grids. Typically, the Grid Control Authority has to purchase the excess power at pre-agreed prices and then ends up selling these off-peak power exports at a major discount. For example, a recent study by the Ontario Association of Professional Engineers reported that over a recent 2 month period, the combined financial loss for the Province of Ontario of selling this power at a discount was $1.25 billion. Although the Province of Ontario is an extreme example of excess clean power production, future efforts to eliminate fossil fuel and peak-power production will most likely result in excess clean power being available in off-peak periods.

[0080] In the building energy system as described herein, a plurality of homes may each comprise a home controller that can communicate with a central server over a communication network. The home controllers may be configured to estimate an amount of electricity that can be used and or stored by elements of the home in the future. The amount of additional electricity may be communicated to a central server that can coordinate consumption of multiple homes to maximize the use of clean power. For example, in homes with thermal storage capacity, the home controller can estimate an additional amount of thermal energy that can be stored in hot and cold thermal storage and then estimate an additional amount of electrical power that would be consumed by an electric heat pump to provide the additional thermal energy to the thermal storage. The home controller may also estimate an additional amount of electricity that may be stored in a battery of the home, and/or used for charging an electric vehicle of the home. This excess load capacity may be communicated by the home controller to the central server. The home controller can transmit an additional load capacity message over the communication network indicative of the additional amount of electric power that can be consumed. The central server may receive the additional load capacity messages from one or more of the plurality of homes and provide messages to one or more of the home controllers providing an indication to increase the electricity consumption during times when no fossil fuels are being used. When the home controller receives the consumption increase message, the electric heat pump and other home appliances are operated to consume a portion of the additional electric power.

[0081] The building energy system disclosed herein thus allows for electricity supply to better match electricity demand, in particular during clean power generation, thereby reducing the amount of excess electricity that must be sold at losses or curtailed, as well as reducing the consumption of electricity generated using fossil fuels. The building energy system promotes consumption/storage of electricity at a time when it is produced by non-fossil fuel sources, thereby reducing greenhouse gas emissions.

[0082] The building energy system further provides infrastructure to provide a home owner with financial incentive for consuming additional electrical power that has been generated from non-fossil fuels. In accordance with some aspects of the present disclosure, the central server may be a third party that purchases power from a utility company of the electrical distribution grid during a period when the electricity is generated from non-fossil fuels, and provides a home owner with a financial incentive for consuming the additional electrical power that has been generated from non-fossil fuels such as by providing the homeowner with a credit to a service offered by the third party. The plurality of homes may be provided with a smart electricity meter that meters an amount of electricity received from the electrical distribution gird according to one of a plurality of supply rates so as to track the additional electrical power that is consumed upon receipt of a consumption increase message from the central server that may be operated by a system operator. Regulatory services contracts may be provided by utilities that often include demand and imbedded supply operator dispatch. With aggregated customers, there is an opportunity for revenues from the system operator.

[0083] The building energy systems described herein comprise several sub-systems that further reduce energy consumption and integrate with the home controller to reduce GHGs associated with electricity consumption. Advantageously, the equipment and sub-systems described herein may be retrofitted to existing buildings, thus making it more economical to provide energy efficient buildings with reduced reliance on fossil fuels.

[0084] The home energy system described further herein comprises a thermal storage system that provides hot and cold thermal storage, which may be used as part of a hydronic heating/cooling system as well as for domestic water heating. An electric heat pump may be linked to the hot and cold thermal storage and consumes electricity to heat the hot storage and cool the cold storage simultaneously. The home energy system may also comprise a stand-alone battery and/or an electric vehicle battery that is capable of storing additional electrical power. In this configuration, the home controller can transmit additional load capacity messages to a central server that can control home controllers to increase electricity consumption when there is excess supply of electricity in the utility system that is being produced by non-fossil fuel sources.

[0085] FIG. 13 shows a representation of a building energy system for a plurality of homes. The building energy system depicted in FIG. 13 includes a schematic drawing of a typical electrical power system where various public and private organizations are involved in the production and distribution of electrical power.

[0086] In some jurisdictions like the Province of Ontario, an independent grid control authority 1344 manages the electrical power system. The independent grid control authority 1344 purchases electrical power from a series of large scale power plants that may be publicly or privately owned. Collectively, these power plants provide a generation capacity 1306.

[0087] The power plants generate power by various means, including: fossil fuels 1306a; nuclear 1306b; large scale hydro 1306c; wind farms 1306d, and solar PV farms 1306e. The individual power plants deliver the power produced to a distribution grid 1304 that connects the generation capacity to a series of electrical loads 1302. The distribution grid 1304 may be publicly or privately owned.

[0088] In terms of grid management, the outputs of the nuclear 1306b and large scale hydro plants 1306c are difficult to modulate and so these plants typically produce power on a continuous basis. Because the operation of the large-scale wind 1306d and solar PV farms 1306e are weather dependent, the outputs to the distribution grid 1304 are only intermittent. Generally, the outputs from the fossil fuel plants 1306a are also intermittent when the clean power supplied to the grid is not sufficient to meet peak load demands. Typically, the output from the various power plants are sold to the Grid Control Authority 1344 at pre-agreed prices.

[0089] In managing the electrical system, it is difficult for the grid control authority 1344 to exactly match power demand with power supply and so particularly in off-peak periods, it is often necessary to export power to neighboring utility grids 1308. As has been previously described, the Grid Control Authority 1344 typically has to purchase the excess power at pre-agreed prices and then ends up selling these off-peak power exports at a major discount.

[0090] To achieve ZE performance within the building energy system across the power plants and the plurality of homes, the starting point is typically to radically upgrade the thermal performance of building envelopes (not shown). Once the building thermal load has been radically reduced, the next step is to replace the existing fossil fuel furnace and hot water heater by an electrical heat pump 1312 that is linked to hot and cold storage 1314. To store excess clean power in off peak periods, a home battery storage 1316 may also be installed as well as an optional car battery charger (not shown). Both the thermal storage 1314 and the battery storage 1316 are linked to a programmable building controller 1318 that determines how much excess clean power needs to be stored in off-peak periods.

[0091] For governments to provide incentives for the construction of ZE retrofits, excess clean power produced during off-peak periods may be sold to home owners at specially discounted prices. In accordance with the present disclosure, an additional grid controller 1334 is introduced and this central server is interconnected through an internet communication network 1324 to the grid control authority 1344; to the generation capacity 1306, to the distribution grid 1304 and to the building controllers 1318 of the individual houses 1310.

[0092] For buildings with the appropriate orientation, solar PV panels 1322 on the roof can produce electrical power that can be stored in batteries for later use. If the batteries have been recharged during the night, during the morning peak period and when future sunshine is predicted, the homeowner may sell back at higher prices, the battery power stored during the night. Similarly, if the batteries 1316 are recharged by solar PV panels during the day, the homeowner can sell the stored solar power back to the additional grid controller 1334 but at higher prices during the evening peak period.

[0093] A smart meter 1320 is configured to measure the excess clean power that is purchased at a special discount rate and supplied to the building 1310 during off-peak periods. The smart meter 1320 also measures the power exported to the grid 1304 during peak periods and is sold back at higher time-of-use rates. The smart meter 1320 further measures whether any power is purchased during peak periods and it can be generally assumed that this peak power is generated using fossil fuels. Assuming that minimal peak power is purchased, the smart meter 1320 may document that the building 1310 has achieved ZE performance and that the homeowner continues to qualify for special discount rates for clean off-peak power.

[0094] One function 1326 of the building home controller 1318 is to estimate both the amount of thermal energy 1314 and battery storage 1316 required until the next period when it is projected that excess clean power will be available. The home controller 1318 also estimates the amount of power that will be generated by the solar PV panels 1322 during daylight hours. Based on these estimates, the home controller 1318 can estimate an additional load/generation amount that is available (1328). Generally, the estimates are based on five main factors: 1. Predicated weather forecast and the resulting heating and cooling loads; 2. The potential for solar power generation again based on the predicted weather forecast; 3. Anticipated schedule for recharging the electric car batteries; 4. The number of occupants in the buildings and their scheduled comings and goings; 5. Special events such as visitors, dinner parties, holidays, etc. As events unfold, the programmable home controller 1318 can update its estimates if required. The programmable home controller 1318 is also self-learning with the estimates 1328 increasing in accuracy overtime. The home controller 118 can report additional load/generation to the additional grid controller 1334 (1330). When instructed by the additional grid controller 1334, the home controller 1318 initiates the operation of the heat pump 1312 and battery storage 1316 as well as exporting power from the solar PV panels 1322 or from the battery storage 1316 in response to receiving a load / generation increase instruction (1332).

[0095] An additional and/or alternative option is for the smart meter 1320 to incorporate computational capabilities and instead of the home controller 1318, these enhanced smart meters can carry out some of the key load management tasks. However, with these enhanced smart meters, there would still be a need for a programmable interface that would allow the homeowner to input key information on scheduling, special events etc. The enhanced smart meter 1320 can be linked to load switches (in some cases, at least four load switches) and this would allow the utility company to directly control the operation of all the major residential power loads, including: heat pump / thermal storage; home battery; electric vehicle battery; dish washer, clothes washer / dryer, etc.

[0096] One function 1336 of the additional grid controller 1334 is to aggregate the reports 1330 of the individual home controllers 1318 of both the estimated electric power load before excess clean-power will be available from the distribution grid 1304 and the estimated potential solar PV power generation that can be exported to the grid to determine an aggregate additional load/generation available (1338). The additional grid controller 1334 may purchase excess clean power from the Grid Control authority 1344 or sell additional solar PV power to the Grid Control authority (1340). In some instances, the purchase/sale of the additional load/generation may be carried out when instructed by the grid control authority 1344. The additional grid controller 1334 may also request additional load/generation capabilities from the home controller 1318 (1342), for example if the additional load/generation control 1334 is attempting to determine whether to purchase/sell the additional load/generation capabilities.

[0097] One function 1346 of the grid control authority 1344 may be to report to the additional grid controller 1334 future periods when excess clean power will be available from the grid (1348). The grid control authority 1344 also sells (1350) excess clean power to the additional grid controller 1334 at special discounted prices or alternatively purchases clean power from the additional grid controller 1334 at higher time-of-use pricing.

[0098] The additional grid controller 1334 can be incorporated within the organization of the grid control authority 1344. Alternatively, the additional grid controller 1334 can be incorporated within the organization responsible for operating the distribution grid 1304, which may simplify various activities, including smart meter repair, smart grid reading, utility bill collection, etc.

[0099] In a further embodiment, the additional grid controller 1334 may be incorporated within a third-party organization such as an internet company that has the expertise to manage a cloud-based communications network. One advantage of employing a third party is that additional financial incentives can be offered to the homeowner for consuming excess clean power in off-peak periods and these incentives may be in the form of a credit to a service offered by the third party. For example, an incentive can be provided by a company like Amazon who are an electronic commerce and cloud computing company. As part of a monthly membership, Amazon may offer various benefits that could in part be tied to the purchase of excess clean power.

[0100] Accordingly, the building energy system depicted in FIG. 13 may be used to provide the necessary infrastructure for better matching supply and demand of clean power production so as to reduce the amount of electricity produced by fossil fuels that is consumed by homes.

[0101] It will be appreciated by one of ordinary skill in the art that the system and components shown in Figures 1-13 may include components not shown in the drawings. For simplicity and clarity of the illustration, elements in the figures are not necessarily to scale, are only schematic and are non-limiting of the elements structures. It will be apparent to persons skilled in the art that a number of variations and modifications can be made without departing from the scope of the invention as defined in the claims.

WHAT IS CLAIMED IS:

1. An energy efficient building heating, ventilation and air conditioning (HVAC) system, comprising:

   a thermal energy storage system comprising a hot storage section and a cold storage section;

   an electric heat pump for heating the hot storage section of the thermal energy storage system and cooling the cold storage section of the thermal energy storage system; and

   a fast response radiant hydronic heating/cooling system to circulate a heat transfer liquid heated or cooled by the thermal energy storage system.

2. The energy efficient building HVAC system of claim 1, wherein the thermal energy storage comprises:

   a hot storage vessel for comprising a first phase change material that changes from a solid to a liquid at or above about 50°C; and

   a cold storage vessel comprising a second phase change material that changes from a liquid to a solid at or below about 0°C.

3. The energy efficient building HVAC system of claim 2, wherein the heat pump comprises a non-reversing electric heat pump that simultaneously heats the first phase change material in the hot storage vessel and cools the second phase change material in the cold storage vessel.

4. The energy efficient building HVAC system of claim 2 or 3, wherein the cold storage vessel contains water which is converted to ice as heat is extracted by the heat pump and where the hot storage vessel contains a phase change material that transitions from a solid to a liquid above 50°C.

5. The energy efficient building HVAC system of claim 4, wherein the phase change material in the hot storage vessel is paraffin wax.

6. The energy efficient building HVAC system of claim 5, wherein the hot storage vessel is a shipping container and where a heat exchanger is pre-installed in the paraffin wax.

7. The energy efficient building HVAC system of any one of claims 2 to 6, wherein the water in the cold storage vessel is provided in pre-filled hollow balls.

8. The energy efficient building HVAC system of claim 7, wherein a casing of the hollow balls is made from metal.

9. The energy efficient building HVAC system of claims 1 to 8, wherein the thermal energy storage system comprises a stratified storage tank.

10. The energy efficient building HVAC system of any one of claims 1 to 9, further comprising a building controller for controlling operation of the non-reversing electric heat pump, the building controller communicatively coupled to a communication network, wherein the building controller controls operation of the non-reversing electric heat pump based at least in part on an indication received over the communication network that electricity supply is generated from non-fossil fuel sources.

11. The energy efficient building HVAC system of claim 10, wherein the fast response heating/cooling system comprises:

radiant hydronic panels disposed in any one of a floor, wall, or ceiling of a room in the building for radiating heat into or absorbing heat from the room;

hydronic piping configured to carry the heat transfer liquid heated or cooled by the thermal energy storage system to an inlet of the radiant hydronic panels and carry the heat transfer liquid from an outlet of the radiant hydronic panels to the electric heat pump, the hydronic piping further comprising:

a pump for pumping the heat transfer liquid through the hydronic piping; and

a valve for controlling flow of the heat transfer liquid through the radiant hydronic panels; and wherein the building controller is further configured to control opening and closing of the valve according to a predetermined fast response operation to provide a desired room temperature.

12. The energy efficient building HVAC system of claim 11, wherein the predetermined fast response operation performed by the building controller controls the valve to open and close repeatedly to pulse the heat transfer liquid into the radiant hydronic panels until a room's operative temperature reaches the desired operative temperature.

13. The energy efficient building HVAC system of claim 11 or 12, wherein the building controller controls the valve to open for a first period of time during the predetermined fast response operation such that a volume of the heat transfer liquid within the radiant hydronic panels is entirely displaced.

14. The energy efficient building HVAC system of any one of claims 11 to 13, wherein the building controller controls the valve to be closed for a second period of time during the predetermined fast response operation, the second period of time increasing in duration each time that the valve is closed.

15. The energy efficient building HVAC system of claim 14, wherein the second period of time is selected to allow a temperature of the heat transfer liquid within the radiant hydronic panel to approach a panel surface temperature within a pre-set amount.

16. The energy efficient building HVAC system of any one of claims 11 to 15, wherein one or more of the radiant hydronic panels further comprises vapour permeable piping for circulating liquid desiccant through the radiant hydronic panel.

17. The energy efficient building HVAC system of any one of claims 1 to 16, further comprising:

ducting for receiving air from outside into the building at an inlet, transferring the air throughout the building, and exhausting air from the building at an outlet;

a first gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing conducting a liquid desiccant, the first gas-liquid heat exchanger being disposed at the inlet of the ducting; and

a second gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing fluidly coupled to the tubing of the first gas-liquid heat exchanger via a run-around piping loop and conducting the liquid desiccant, the second gas-liquid heat exchanger being disposed at the outlet of the ducting.

18. The energy efficient building HVAC system of claim 17, further comprising a first liquid-liquid heat exchanger, fluidly coupled to the run-around piping loop upstream of the first gas-liquid exchanger, for controlling a temperature of the liquid desiccant, wherein:

heating the liquid desiccant causes water vapour to be expelled from the liquid desiccant at the first gas-liquid exchanger; and

cooling the liquid desiccant causes water vapour to be absorbed by the liquid desiccant at the first gas-liquid exchanger.

19. The energy efficient building HVAC system of claim 18, further comprising a second liquid-liquid heat exchanger, fluidly coupled to the run-around piping loop upstream of the second gas-liquid exchanger, for controlling a temperature of the liquid desiccant, wherein:

heating the liquid desiccant causes water vapour to be expelled from the liquid desiccant at the second gas-liquid exchanger; and

cooling the liquid desiccant causes water vapour to be absorbed by the liquid desiccant at the second gas-liquid exchanger.

20. The energy efficient building HVAC system of claim 19, wherein each of the first and second liquid-liquid heat exchangers is provided with the heat transfer liquid heated or cooled by the thermal energy storage system to heat or cool the liquid desiccant.

21. The energy efficient building HVAC system of any one of claims 17 to 20, wherein the run-around piping loop further comprises a fill tank comprising distilled water for maintaining a level of humidity in the liquid desiccant.

22. The energy efficient building HVAC system of any one of claims 17 to 21, wherein the first and second gas-liquid heat exchangers each comprise:

    an outer enclosure bounding the gas-liquid heat exchanger;

    a perforated air diffuser bounding an inner area of the gas-liquid heat exchanger that receives the air from the ducting, the tubing being arranged around an outer surface of the perforated air diffuser, the tubing comprising inner and outer tubular headers respectively coupled with the run-around piping loop;

    a first plate at a first edge of the outer enclosure that prevents the air from entering into the gas-liquid heat exchanger between the outer enclosure and the inner area; and

    a second plate at a second edge of the outer enclosure that prevents the air from exiting the gas-liquid heat exchanger from the inner area, the perforated air diffuser, and the tubing, the plate defining an outer area for the gas to exit between the outer enclosure and the tubing.

23. The energy efficient building HVAC system of claim 22, wherein the air enters the gas-liquid heat exchanger through a bottom and into the inner area, and flows radially outward through the perforated air diffuser and the tubing to the outer area, and exits through a top of the gas-liquid heat exchanger.

24. The energy efficient building HVAC system of any one of claims 17 to 23, wherein the ducting transfers incoming air to common areas in the building.

25. The energy efficient building HVAC system of any one of claims 17 to 24, wherein each room in the building comprises an outlet through which air is exhausted the room into an adjacent space.

26. The energy efficient building HVAC system of any one of claims 1 to 25, further comprising an operative temperature sensor disposed on a wall of the room where at least one of the radiant hydronic panels is located, the operative temperature sensor determining an operative temperature as an average of air temperature and mean radiant temperature of the at least one radiant hydronic panels.

27. The energy efficient building HVAC system of claim 26, wherein the operative temperature sensor further comprises one or more of:

    an occupancy sensor;
    a touch display screen configured to allow a user to set a desired room temperature;
    a microphone configured to receive voice commands to set the desired room temperature;
    a speaker;
    a communication interface;
    a humidity sensor;
    an air quality sensor;
    a light sensor for measuring ambient light in a room.

28. The energy efficient building HVAC system of any one of claims 27, wherein a desired room temperature is different based on a determined presence of occupants in the room, the desired room temperature being one of a setback room temperature when there are no occupants in the room, and an occupied desired room temperature when there are occupants in the room.

29. The energy efficient building HVAC system of any one of claims 1 to 28, further comprising a geothermal ground loop configured to provide thermal storage to the building.

30. The energy efficient building HVAC system of claim 29, wherein the geothermal ground loop comprises plastic tubing buried at least 25 mm below a frost line.

31. The energy efficient building HVAC system of claim 29 or 30, wherein the geothermal ground loop comprises a multi-building ground loop.

32. The energy efficient building HVAC system of any one of claims 29 to 31, wherein the geothermal ground loop is a thermal energy source/sink to the electric heat pump.

33. The energy efficient building HVAC system of any one of claims 1 to 32, further comprising:

an electrical grid hub that interfaces with an electrical grid to draw electricity from the electrical grid; and

and a building controller configured to:

estimate an amount of additional electrical power useable by the electric heat pump;

receive an indication from a central server to increase electricity consumption in the building by drawing electricity from the electrical grid; and

operate the electric heat pump to consume the amount of additional electrical power.

34. The energy efficient building HVAC system of claim 33, further comprising one or more batteries for storing excess electricity, and wherein the building controller is further configured to:

estimate an amount of additional electrical power capable of being stored in the one or more batteries; and

in response to receiving the indication to increase electricity consumption, cause the one or more batteries to store the amount of additional electrical power.

35. The energy efficient building HVAC system of claim 33 or 34, further comprising one or more vehicles being plugged-in for charging a rechargeable battery of the one or more vehicles, and wherein the building controller is further configured to:

estimate an amount of additional electrical power capable of being stored in the rechargeable battery of the one or more vehicles; and

in response to receiving the indication to increase electricity consumption, cause the rechargeable battery to consume the amount of additional electrical power.

36. The energy efficient building HVAC system of any one of claims 33 to 35, wherein the central server is provided by a utility company that provides electricity to the electrical grid.

37. The energy efficient building HVAC system of any one of claims 33 to 35, wherein the central server is provided by a third party that distributes electricity via the electrical grid.

38. The energy efficient building HVAC system of any one of claims 33 to 37, wherein the grid hub comprises a smart meter that measures an amount of electricity received from the electrical grid and consumed by the building.

39. The energy efficient building HVAC system of claim 38, wherein the smart meter is further configured to measure the amount of additional electrical power received from the electrical grid and consumed by the building.

40. The energy efficient building HVAC system of claim 39, wherein the smart meter is further configured to send the measured amount of additional electrical power received from the electrical grid and consumed by the building to the central server.

41. The energy efficient building HVAC system of any one of claims 33 to 40, wherein the building controller controls the grid hub to draw the electricity from the grid only at predefined times when the electricity in the grid is produced by renewable energy sources.

42. The energy efficient building HVAC system of any one of claims 33 to 41, wherein the indication from the central server to increase electricity consumption in the building is received when electricity in the electrical grid is being produced by non- fossil fuel sources.

43. The energy efficient building HVAC system of any one of claims 33 to 42, wherein the grid hub measures and records GHG emissions caused by the building's operation.

44. A thermal storage system comprising:

thermal energy storage comprising:

a hot storage vessel for comprising a first phase change material that changes from a solid to a liquid at or above about 50°C; and

a cold storage vessel comprising a second phase change material that changes from a liquid to a solid at or below about 0°C;

a non-reversing electric heat pump that simultaneously heats the first phase change material in the hot storage vessel and cools the second phase change material in the cold storage vessel; and

a building controller for controlling operation of the non-reversing electric heat pump, the building controller communicatively coupled to a communication network, wherein the building controller controls operation of the non-reversing electric heat pump based at least in part on an indication received over the communication network that electricity supply is generated from non-fossil fuel sources.

45. The thermal storage system of claim 44, wherein the cold storage vessel contains water which is converted to ice as heat is extracted by the heat pump and wherein the hot storage vessel contains a phase change material that transitions above 50°C.

46. The thermal storage system of claim 45, wherein the water in the cold storage vessel is provided in pre-filled hollow balls.

47. The thermal storage system of claim 46, wherein a casing of the hollow balls is made from metal.

48. The thermal storage system of any one of claims 44 to 47, wherein the phase change material in the hot storage vessel is paraffin wax.

49. The thermal storage system of claim 48, wherein the hot storage vessel is a shipping container and where a heat exchanger is pre-installed in the paraffin wax.

50. The thermal storage system of any one of claims 44 to 49, wherein in order to maintain the second phase change material in the cold storage vessel above freezing during a heating season, the cold storage is provided with heat from a ground heat exchanger and a waste water heat exchanger

51. The thermal storage system of claim 50, wherein the ground heat exchanger comprises plastic tubing located around a perimeter of the building and buried at least 25 mm below a frost line.

52. The thermal storage system of claim 50 or 51, wherein the ground heat exchanger is operated intermittently to allow ground surrounding the piping to be reheated or re-cooled from deeply located geothermal sources.

53. The thermal storage system of any one of claims 44 to 52, wherein additional heat can be transferred to the cold storage vessel by space cooling of overheated rooms in the building.

54. The thermal storage system of any one of claims 44 to 53, wherein a domestic hot water supply to the building is heated using heat from the hot storage vessel.

55. The thermal storage system of any one of claims 33 to 54, wherein heat from the hot storage vessel is used to drive-off moisture from a liquid desiccant material.

56. The thermal storage system of any one of claims 44 to 55, wherein during a cooling season, the heat pump extracts heat from the cold storage vessel and where the cold storage vessel receives heat from multiple radiant cooling hydronic devices.

57. The thermal storage system of any one of claims 44 to 56, wherein during the cooling season, the heat pump extracts heat from the cold storage vessel and where the cold storage vessel receives heat from a liquid desiccant dehumidification system.

58. The thermal storage system of any one of claims 44 to 57, wherein heat from the hot storage vessel is used to preheat a water supply entering the building.

59. The thermal storage system of any one of claims 44 to 58, wherein during the cooling season, heat from the hot storage vessel is mixed with a cold-water supply to the building and used for irrigation purposes.

60. The thermal storage system of any one of claims 44 to 59, wherein cooling loads are insufficient to melt the ice, heat is supplied to the cold storage vessel from waste water heat exchangers, ground source heat exchangers and from other sources of low-grade heat.

61. The thermal storage system of any one of claims 44 to 60, wherein the building's space conditioning load including ventilation air are met by means of a 4-pipe hydronic distribution system capable of simultaneously providing the multiple hydronic radiant heating devices with both hot and cold liquids supplied from the hot and cold storage vessels.

62. The thermal storage system of any one of claims 44 to 60, wherein 6-port, motorized heat/cool switch valve for each respective radiant hydronic device is used to separately supply each device with heating or cooling liquids directly from the hot and cold storage vessels.

63. The thermal storage system of any one of claims 44 to 62, wherein a series of small room pumps are used to individually supply each hydronic radiant device with hot or cold liquid.

64. The thermal storage system of any one of claims 44 to 63, wherein a series of voice-activated room controllers control the operation of multiple hydronic radiant devices that are located in each room or zone of the building enclosure.

65. The thermal storage system of claim 64, wherein comfort conditions in each room or zone can be rapidly and selectively varied by means of a voice-activated room controller that controls the operation of a small room pump and also the operation of a 6-port motorized heat/cool switch valve.

66. The thermal storage system of claim 65, wherein if a room is scheduled to be unoccupied for an extended period of time, a room temperature can be reduced or increased to a set background heating or cooling temperatures with collected hot or cold thermal energy being transferred back to the respective hot or cold storage vessel.

67. A building energy management system, comprising:

a plurality of buildings connected to an electrical distribution grid, each building comprising:

a hydronic heating/cooling system;

a thermal storage system coupled to the hydronic heating/cooling system and providing hot and cold thermal storage;

an electric heat pump linked to the hot and cold thermal storage of the thermal storage system; and

a building controller operatively coupled to a communication network, the building controller configured to:

estimate an amount of additional thermal energy that may be stored by the hot and cold thermal storage;

estimate an additional amount of electrical power based on the electricity that would be consumed by the electric heat pump to supply the additional thermal energy;

transmit an additional load capacity message over the communication network indicative of the additional amount of electrical power;

subsequent to transmitting the additional load capacity message, receive a consumption increase message providing an indication to increase electricity consumption in the building; and

operate the electric heat pump to consume at least a portion of the additional electrical power; and

a central server operatively coupled to the communication network, the central server configured to:

receive respective additional load capacity messages from one or more of the plurality of buildings;

determine an aggregate amount of available load capacity based on the received additional load capacity messages;

determine if electricity supply is currently generated from non-fossil fuels; and

transmit to the one or more buildings respective consumption increase messages providing the indication to increase electricity consumption.

68. The system of claim 67, wherein at least one of the plurality of buildings further comprises a storage battery for storing excess electricity, and wherein the building controller is further configured to:

estimate an amount of electrical power capable of being stored in the battery; and

wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the battery.

69. The system of claim 67 or 68, wherein at least one of the plurality of buildings further comprises a vehicle comprising a rechargeable battery, and wherein the building controller is further configured to:

estimate an amount of electrical power capable of being stored in the vehicle's battery; and

wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the vehicle's battery.

70. The system of any one of claims 67 to 69, wherein the central server is provided by a utility company of the electrical distribution grid.

71. The system of any one of claims 67 to 69, wherein the central server is provided by a third party that purchases power from a utility company of the electrical distribution grid during a period when the electricity is generated from non-fossil fuels.

72. The system of claim 71, wherein the third party receives an indication of an amount of excess electricity supply available from a utility company that provides electricity to the electrical distribution grid.

73. The system of claim 71, wherein the third party provides a building owner with a financial incentive for consuming the additional electrical power that has been generated from non-fossil fuels.

74. The system of claim 73, wherein the financial incentive comprises a credit to a service offered by the third party.

75. The system of any one of claims 67 to 74, wherein one or more of the plurality of buildings further comprises a smart electricity meter that is directly linked to a load switch and that meters an amount of electricity received from the electrical distribution grid.

76. The system of claim 75, wherein the smart electricity meter is further configured to meter the electricity according to one of a plurality of supply rates.

77. A building energy system, comprising:

a hydronic heating/cooling system;

a thermal storage system coupled to the hydronic heating/cooling system and providing hot and cold thermal storage;

an electric heat pump linked to the hot and cold thermal storage of the thermal storage system; and

a building controller operatively coupled to a communication network, the building controller configured to:

estimate an amount of additional thermal energy that may be stored by the hot and cold thermal storage and a corresponding additional amount of electrical power that could be consumed by the electric heat pump to supply the additional thermal energy;

transmit an additional load capacity message over the communication network indicative of the additional amount of electrical power that could be consumed;

subsequent to transmitting the additional load capacity message, receive a consumption increase message providing an indication to increase electricity consumption in the building, the consumption increase message provided during a time when electricity is being generated from non-fossil-fuel sources; and

operate the electric heat pump to consume the amount of additional electrical power.

78. The building energy system of claim 77, further comprising a storage battery for storing excess electricity, and wherein the building controller is further configured to:

estimate an amount of electrical power capable of being stored in the battery; and
wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the battery.

79. The building energy system of claim 77, further comprising a vehicle comprising a rechargeable battery, and wherein the building controller is further configured to:

estimate an amount of electrical power capable of being stored in the vehicle's battery; and
wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the vehicle's battery.

80. The building energy system of any one of claims 77 to 79, wherein the central server is provided by a utility company of the electrical distribution grid.

81. The building energy system of any one of claims 77 to 79, wherein the central server is provided by a third party that purchases power from a utility company of the electrical distribution grid during a period when the electricity is generated from non-fossil fuels.

82. The building energy system of claim 81, wherein the third party receives an indication of an amount of excess electricity supply available from a utility company that provides electricity to the electrical distribution grid.

83. The building energy system of claim 81 or 82, wherein the third party provides a building owner with a financial incentive for consuming the additional electrical power that has been generated from non-fossil fuels.

84. The building energy system of claim 83, wherein the financial incentive comprises a credit to a service offered by the third party.

85. The building energy system of any one of claims 77 to 84, further comprising a smart electricity meter that is directly linked to a load switch and that meters an amount of electricity received from the electrical distribution grid.

86. The building energy system of claim 85, wherein the smart meter is further configured to meter the electricity according to one of a plurality of supply rates.

87. A method of operating a heat pump in a building to reduce consumption of fossil fuels, the method performed by a building controller and comprising:

estimating an amount of additional thermal energy that may be stored by hot and cold thermal storage in the building;

estimating an additional amount of electrical power based on the electricity that would be consumed by an electric heat pump to supply the additional thermal energy;

transmitting an additional load capacity message over a communication network indicative of the additional amount of electrical power;

subsequent to transmitting the additional load capacity message, receiving a consumption increase message providing an indication to increase electricity consumption in the building; and

operating the electric heat pump to consume at least a portion of the additional electrical power.

88. The method of claim 87, further comprising:

estimating an amount of electrical power capable of being stored in a battery within the building; and

wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the battery.

89. The method of claim 87 or 88, further comprising:

estimating an amount of electrical power capable of being stored in a battery of a vehicle plugged into an electrical panel of the building; and

wherein estimating the additional amount of electrical power is further based on the estimated amount of electrical power for storage in the vehicle’s battery.

90. The method of any one of claims 87 to 89, wherein the additional load capacity message is provided to a central server provided by a utility company of an electrical distribution grid.

91. The method of any one of claims 87 to 90, wherein the additional load capacity message is provided to a central server provided by a third party that purchases power from a utility company of the electrical distribution grid during a period when the electricity is generated from non-fossil fuels.

92. The method of claim 91, wherein the third party receives an indication of an amount of excess electricity supply available form a utility company that provides electricity to the electrical distribution grid.

93. The method of claim 91 or 92, wherein the third party provides a building owner with a financial incentive for consuming the additional electrical power that has been generated from non-fossil fuels.

94. The method of claim 93, wherein the financial incentive comprises a credit to a service offered by the third party.

95. The method of claim 90 to 94, further comprising:

receiving, at the central server, a plurality of additional load capacity messages; and
determining an aggregate amount of available load capacity based on the received additional load capacity messages.

96. The method of claim 95, further comprising:

determining, by the central server, an amount of excess electricity supply in the electrical grid; and
transmitting, from the central server, an instruction comprising the indication to increase electricity consumption of the building in accordance with the amount of excess electricity in the electrical grid.

97. A fast response radiant hydronic heating/cooling system for a building, comprising:

radiant hydronic panels disposed in any one of a floor, wall, or ceiling of a room in the building for radiating heat into or absorbing heat from the room;

hydronic piping configured to carry a heat transfer liquid heated or cooled by a thermal energy storage system to an inlet of the radiant hydronic panels and carry the heat transfer liquid from an outlet of the radiant hydronic panels to an electric heat pump, the hydronic piping further comprising:

a pump for pumping the heat transfer liquid through the hydronic piping; and

a valve for controlling flow of the heat transfer liquid through the radiant hydronic panels; and

wherein a building controller is configured to control opening and closing of the valve according to a predetermined fast response operation to provide a desired room temperature.

98. A method of determining if heating/cooling of a room in a building is required, comprising:

receiving a setting of a desired room temperature including a background desired room temperature and an occupied desired room temperature;

receiving sensor data indicating a current room temperature;

receiving sensor data indicating whether the room is occupied; and

determining if heating/cooling of the room is required by:

if the room occupied, calculating a difference between the current room temperature and the occupied desired room temperature, wherein if the difference is greater than a first predefined threshold value, heating/cooling of the room is required; and

if the room is unoccupied, calculating a difference between the current temperature and the background room temperature, wherein if the difference is greater than a second predefined threshold value, heating/cooling of the room is required.

99. A method of heating/cooling a room in a house that comprises a radiant hydronic heating/cooling system, comprising:

receiving an instruction to perform a fast response operation for rapid heating/cooling of the room using the radiant hydronic heating/cooling system; and repeatedly opening and closing a valve that regulates a flow of a heat transfer liquid to radiant hydronic panels of the radiant heating/cooling system until a desired room temperature is reached,

wherein the repeated opening and closing of the valve comprises:

opening the valve for a first period of time to entirely displace a volume of the heat transfer liquid within the radiant hydronic panels; and

closing the valve for a second period of time to promote radiant heat transfer with the volume of the heat transfer liquid within the hydronic radiant manifolds;

wherein each time that the valve is closed, the second period of time increases in duration.

100. A displacement ventilation system for a building, comprising:

ducting for receiving air from outside into the building at an inlet, transferring the air throughout the building, and exhausting air from the building at an outlet;

a first gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing conducting a liquid desiccant, the first gas-liquid heat exchanger being disposed at the inlet of the ducting; and

a second gas-liquid heat exchanger comprising small-diameter, vapour-permeable, liquid-tight tubing fluidly coupled to the tubing of the first gas-liquid heat exchanger via a run-around piping loop and conducting the liquid desiccant, the second gas-liquid heat exchanger being disposed at the outlet of the ducting.

101. An enthalpy heat exchanger, comprising:

a housing having an input and an output connected by a heat exchange section for conducting a heat exchange medium; and

a length of small-diameter, vapour-permeable, liquid-tight tubing connecting a first port and a second port for conducting a liquid desiccant, the tubing in thermal contact with the heat exchange section.

102. The enthalpy heat exchanger of claim 101, wherein the enthalpy heat exchanger is an air-to-liquid enthalpy heat exchanger and the heat exchange medium is air.

103. The enthalpy heat exchanger of claim 102, wherein the enthalpy heat exchanger is a liquid-to-liquid enthalpy heat exchanger provided in a radiant hydronic panel.

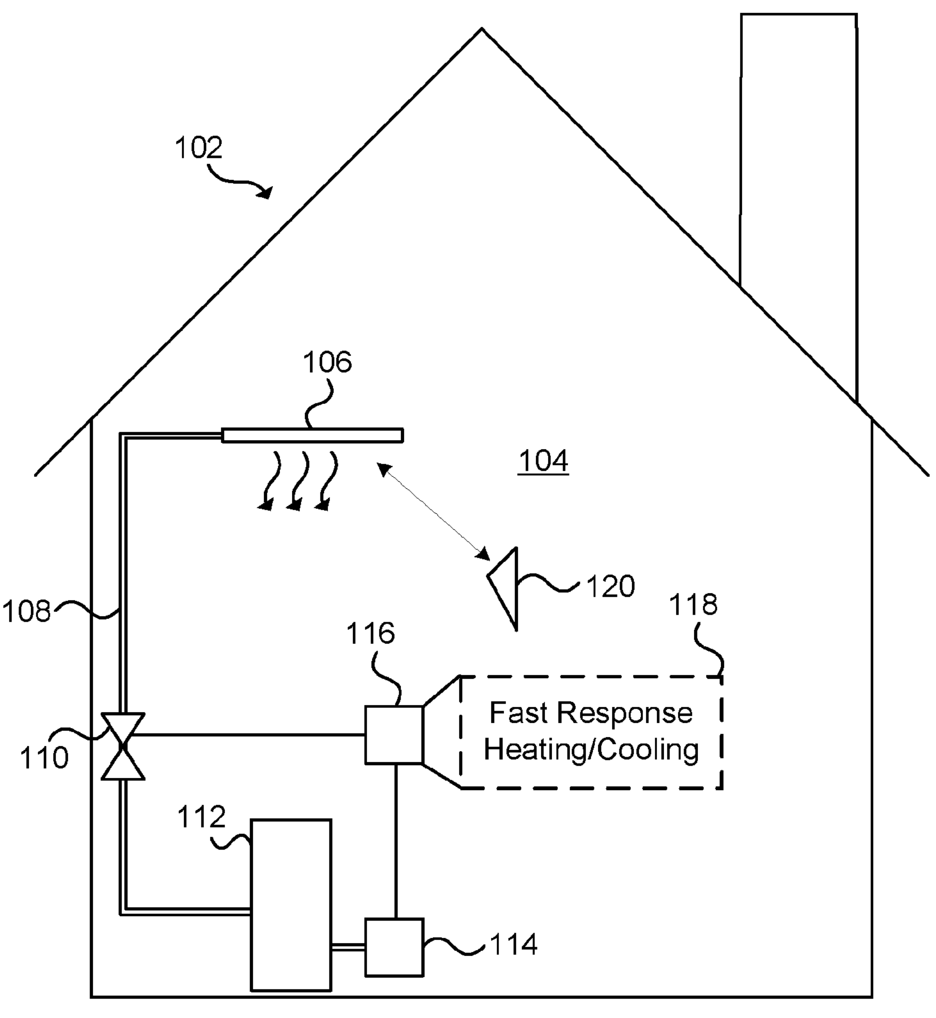
102
106
104
120
118
108
116
Fast Response
Heating/Cooling
110
112
114

FIG. 1

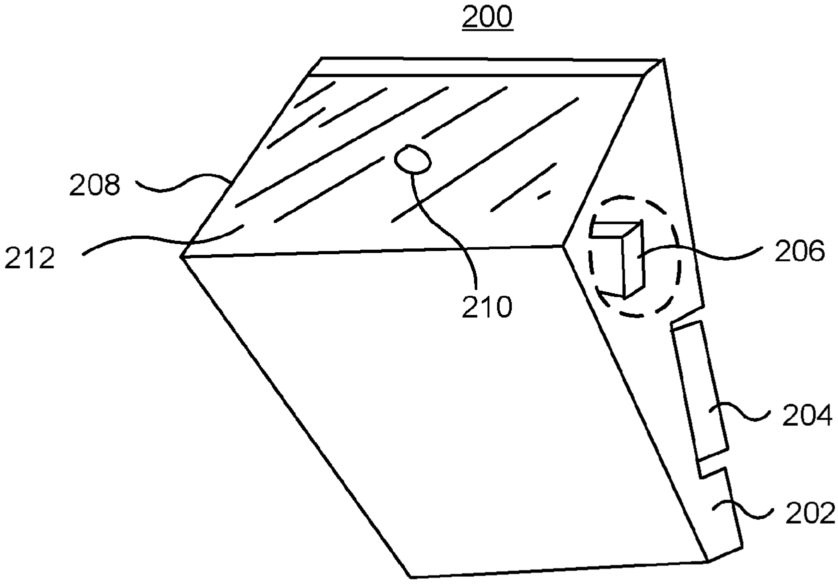

FIG. 2A

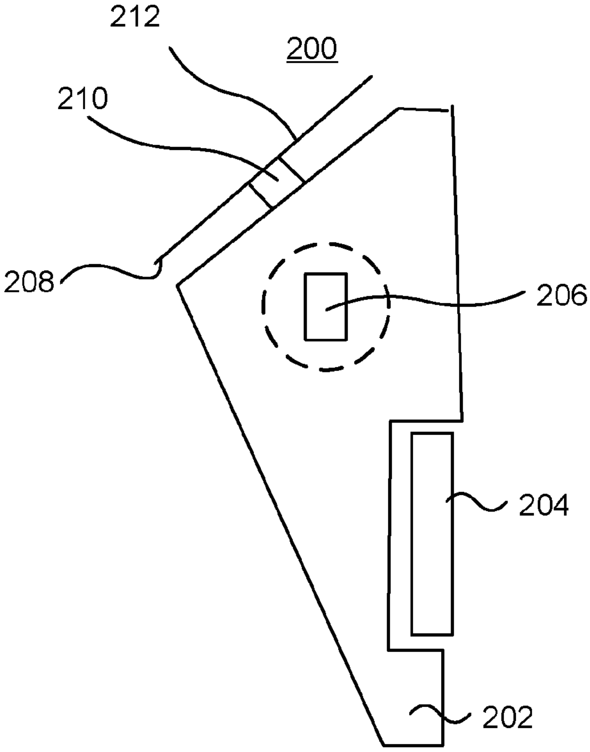

FIG. 2B

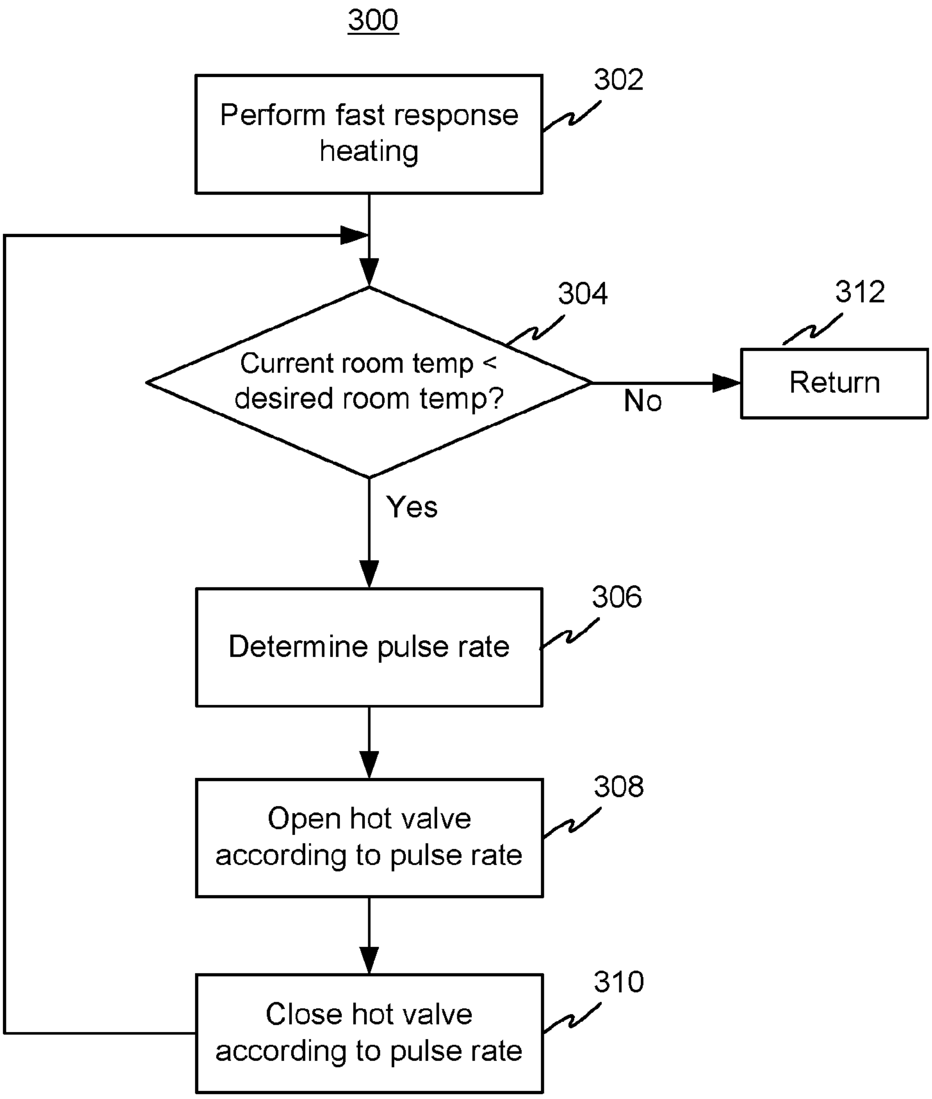
300
Perform fast response heating
302
Current room temp < desired room temp?
304
No
Return
312
Yes
Determine pulse rate
306
Open hot valve according to pulse rate
308
Close hot valve according to pulse rate
310

FIG. 3

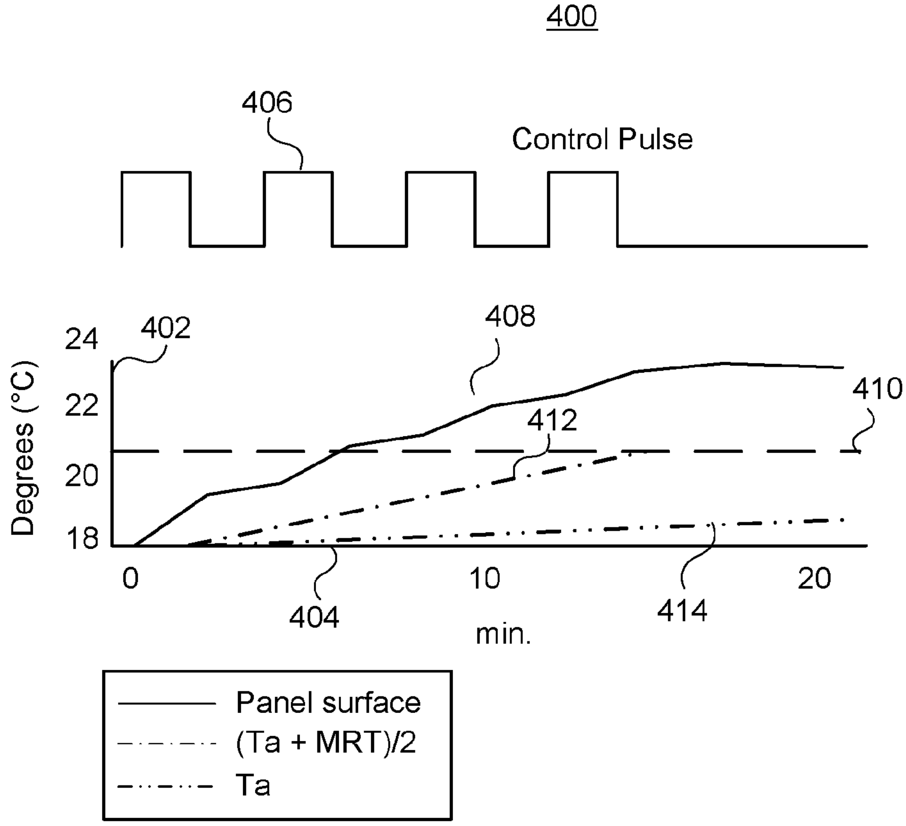
400
406
Control Pulse
24
402
408
22
410
412
Degrees (°C)
20
18
0
10
20
404
414
min.
Panel surface
(Ta + MRT)/2
Ta

FIG. 4

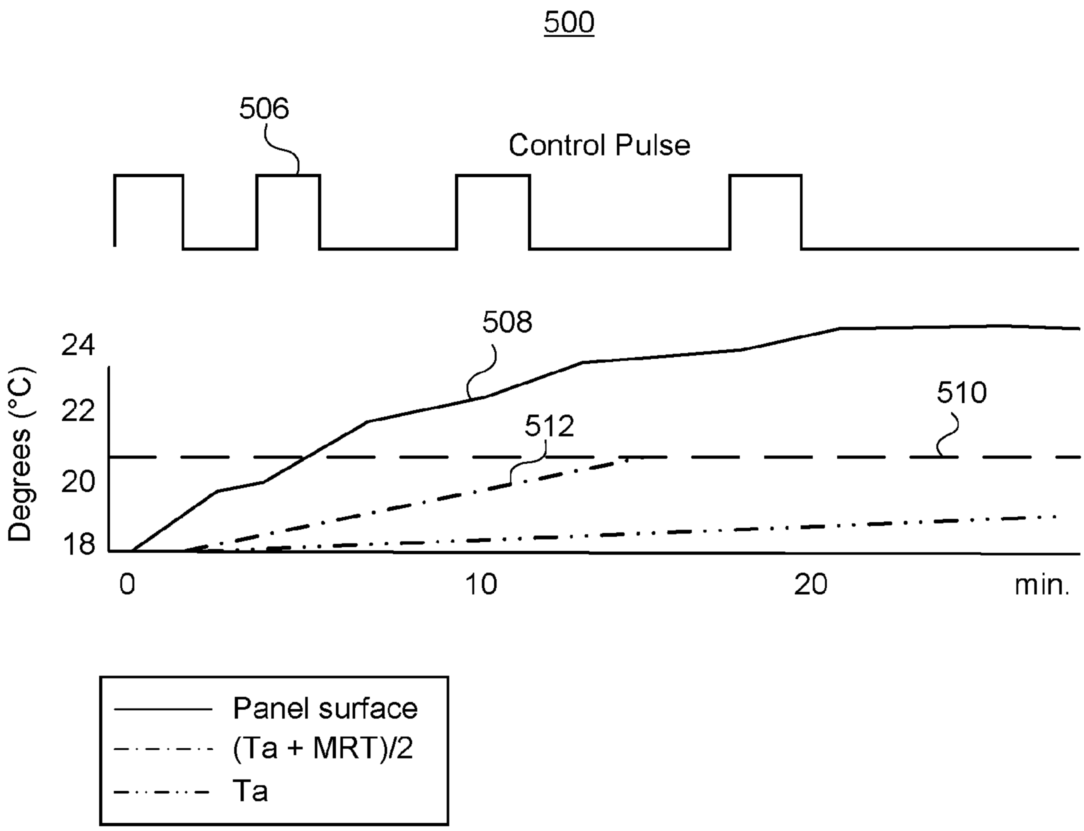
500
506
Control Pulse
508
510
512
24
22
20
18
Degrees (°C)
0
10
20
min.
Panel surface
(Ta + MRT)/2
Ta

FIG. 5

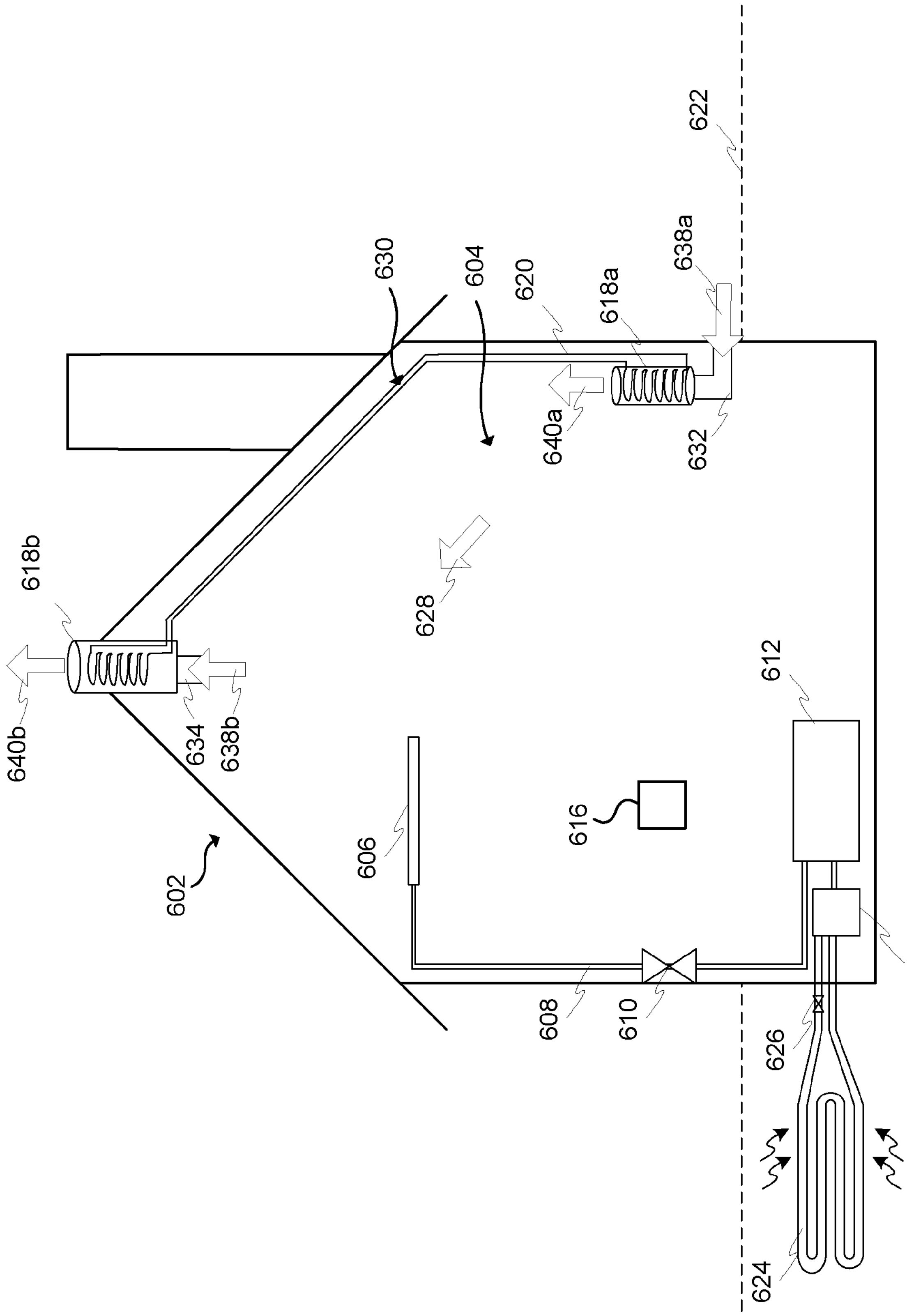
622
630
604
620
618a
638a
640a
632
618b
628
640b
634
638b
612
616
606
602
614
608
610
626
624

FIG. 6

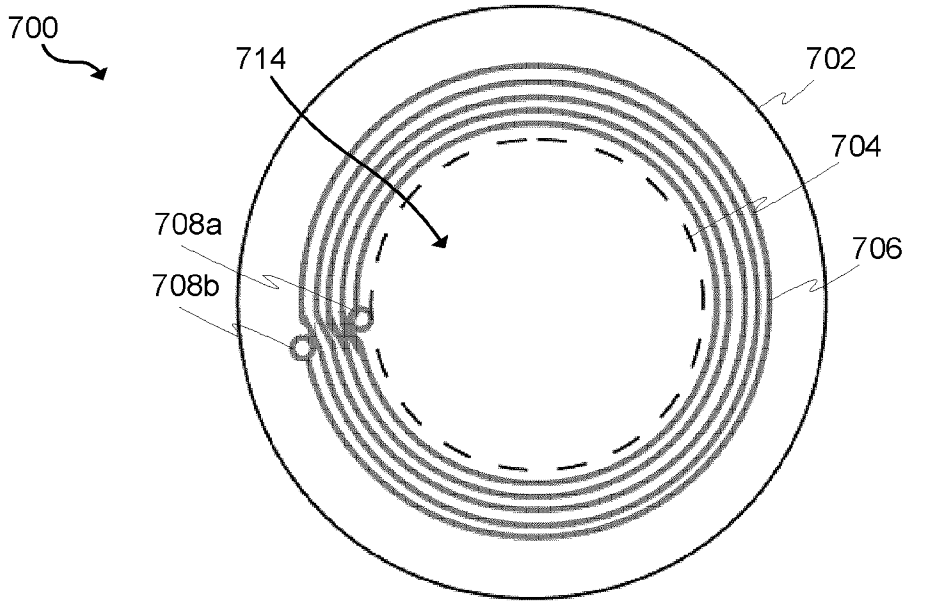

FIG. 7A

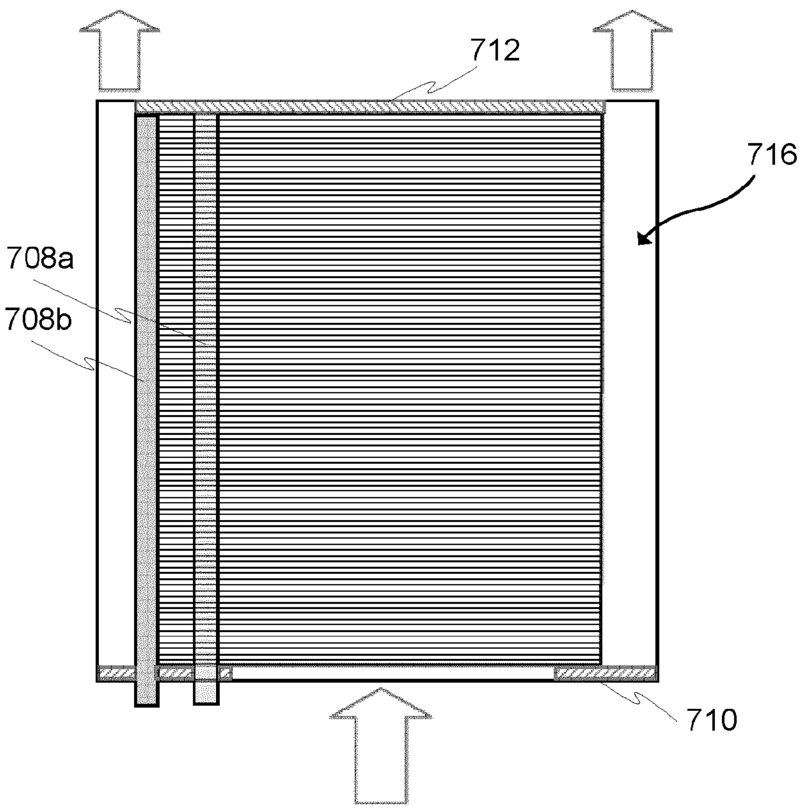

FIG. 7B

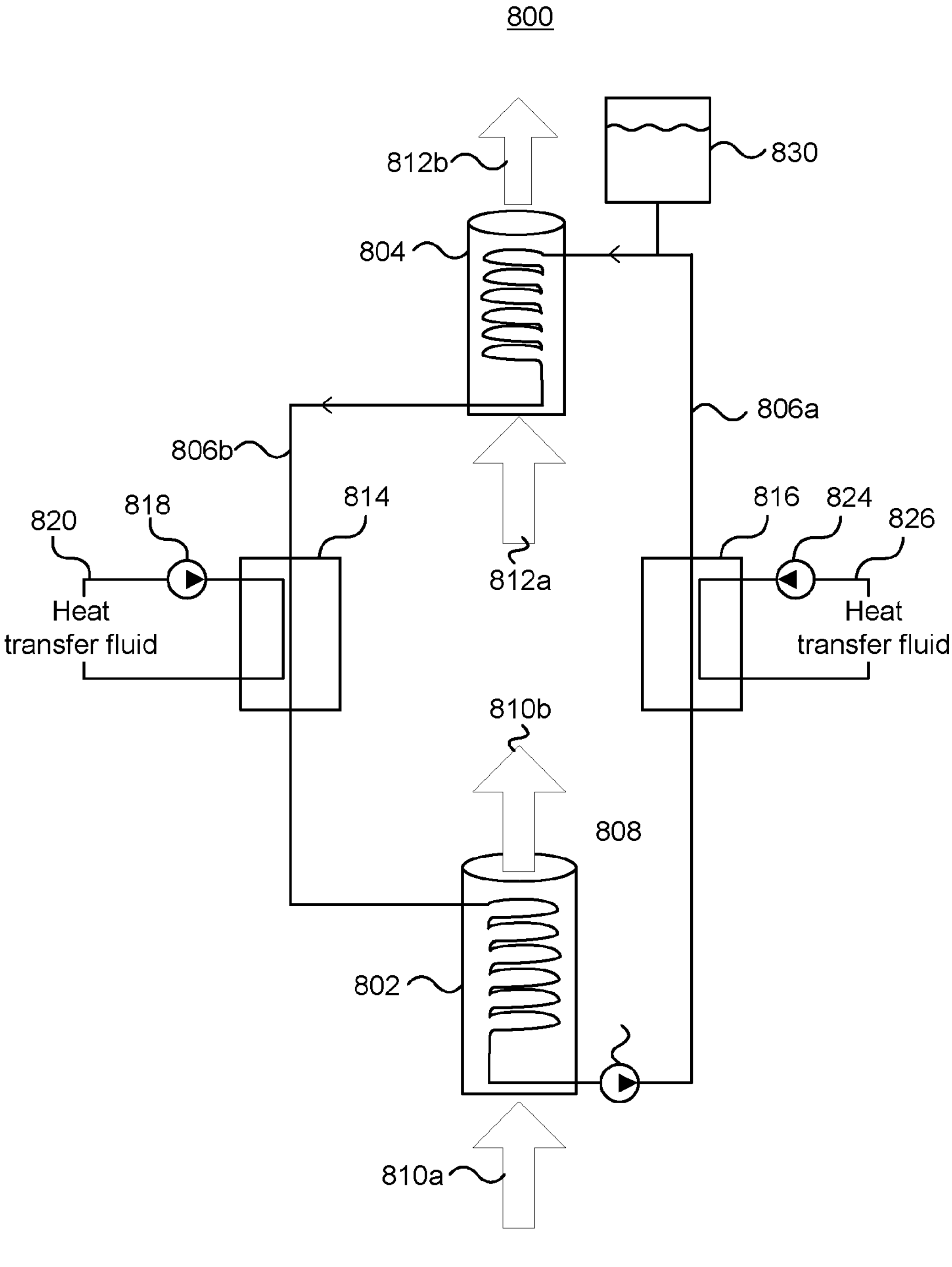
800
812b
830
804
806a
806b
820
818
814
812a
816
824
826
Heat
transfer fluid
Heat
transfer fluid
810b
808
802
810a

FIG. 8

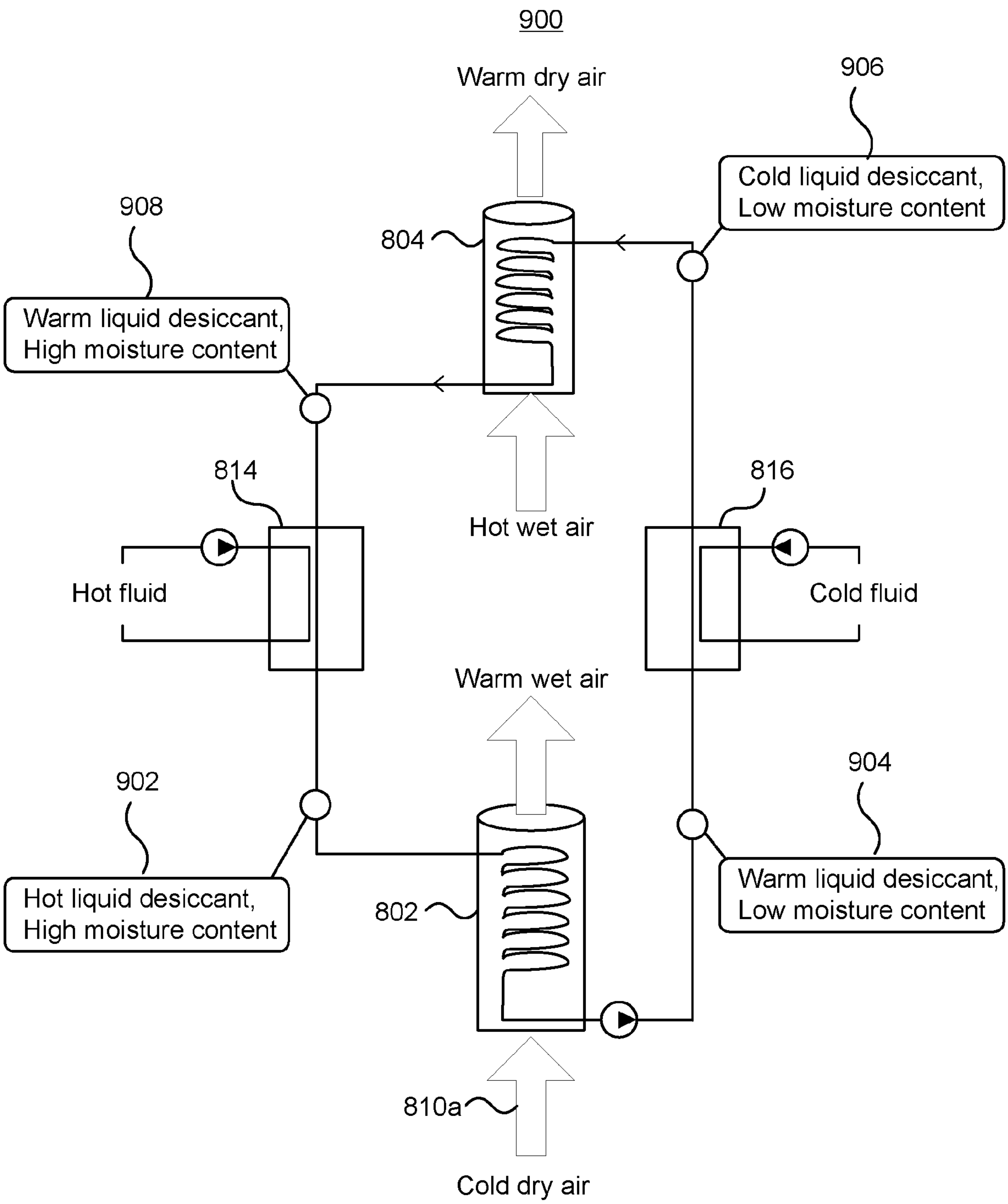
900
Warm dry air
906
Cold liquid desiccant,
Low moisture content
908
804
Warm liquid desiccant,
High moisture content
814
Hot wet air
816
Hot fluid
Cold fluid
Warm wet air
904
902
Warm liquid desiccant,
Low moisture content
Hot liquid desiccant,
High moisture content
802
810a
Cold dry air

FIG. 9

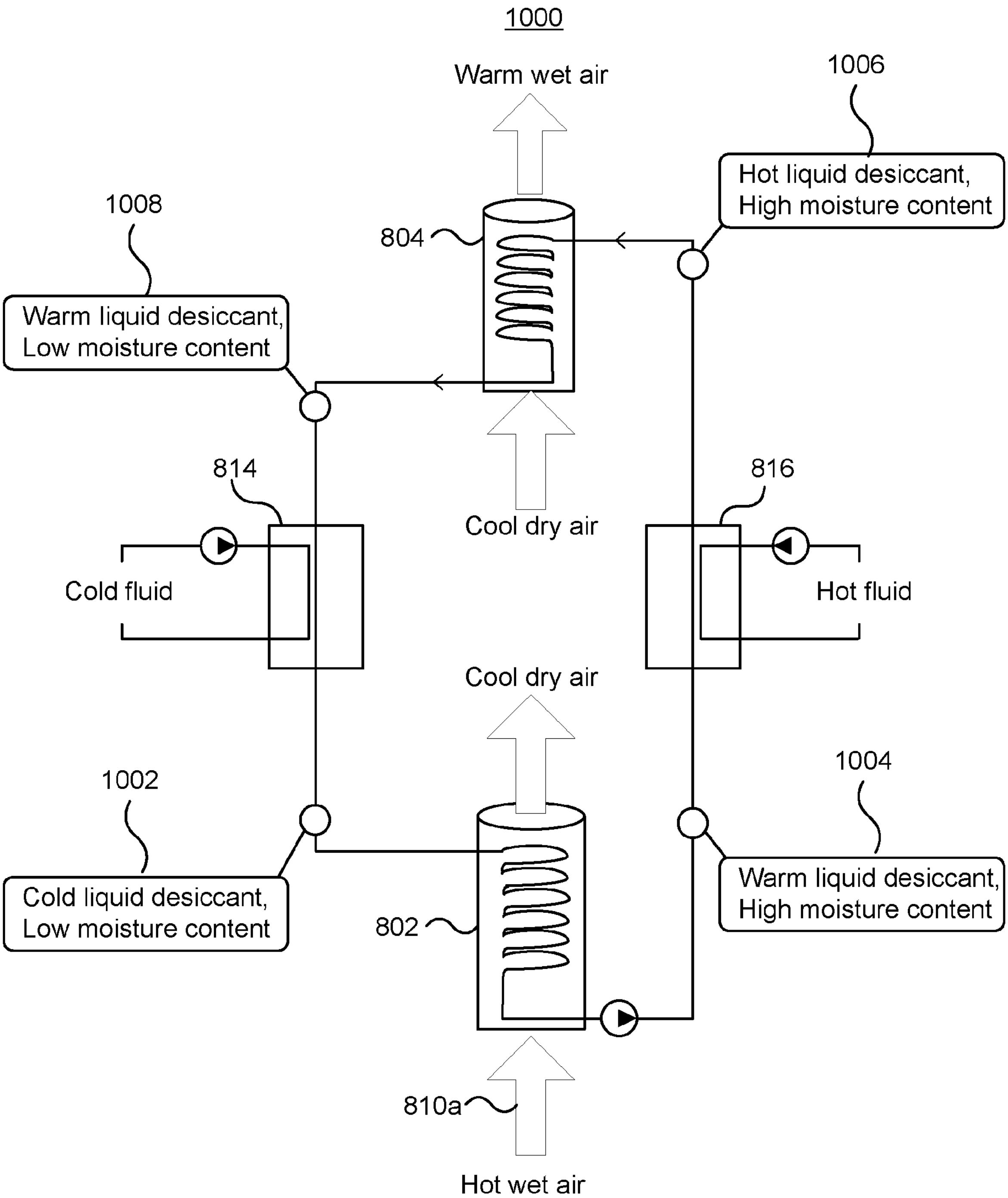
1000
Warm wet air
1006
Hot liquid desiccant,
High moisture content
1008
804
Warm liquid desiccant,
Low moisture content
814
816
Cool dry air
Cold fluid
Hot fluid
Cool dry air
1002
1004
Cold liquid desiccant,
Low moisture content
Warm liquid desiccant,
High moisture content
802
810a
Hot wet air

FIG. 10

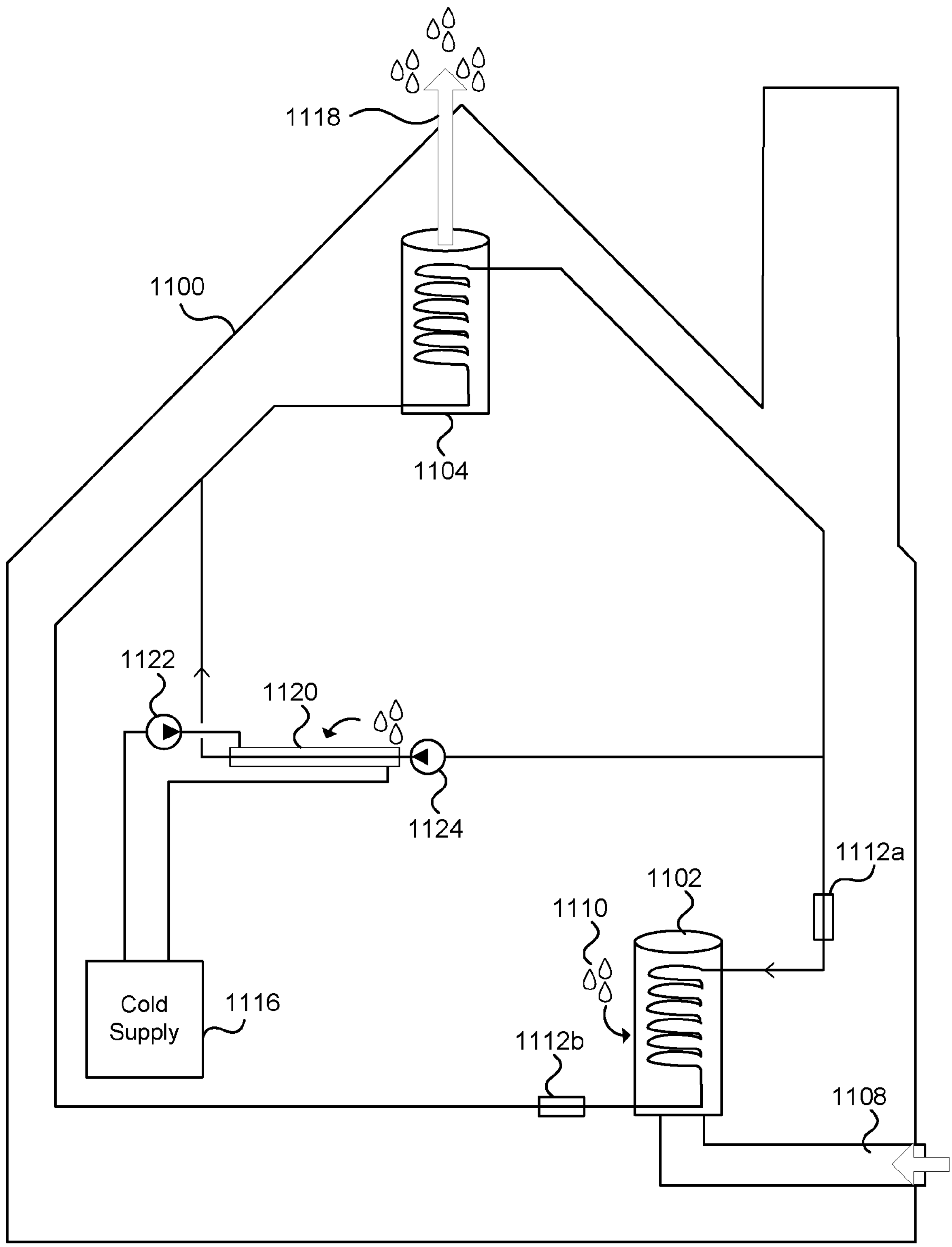
1118
1100
1104
1122
1120
1124
1112a
1102
1110
Cold Supply
1116
1112b
1108

FIG. 11

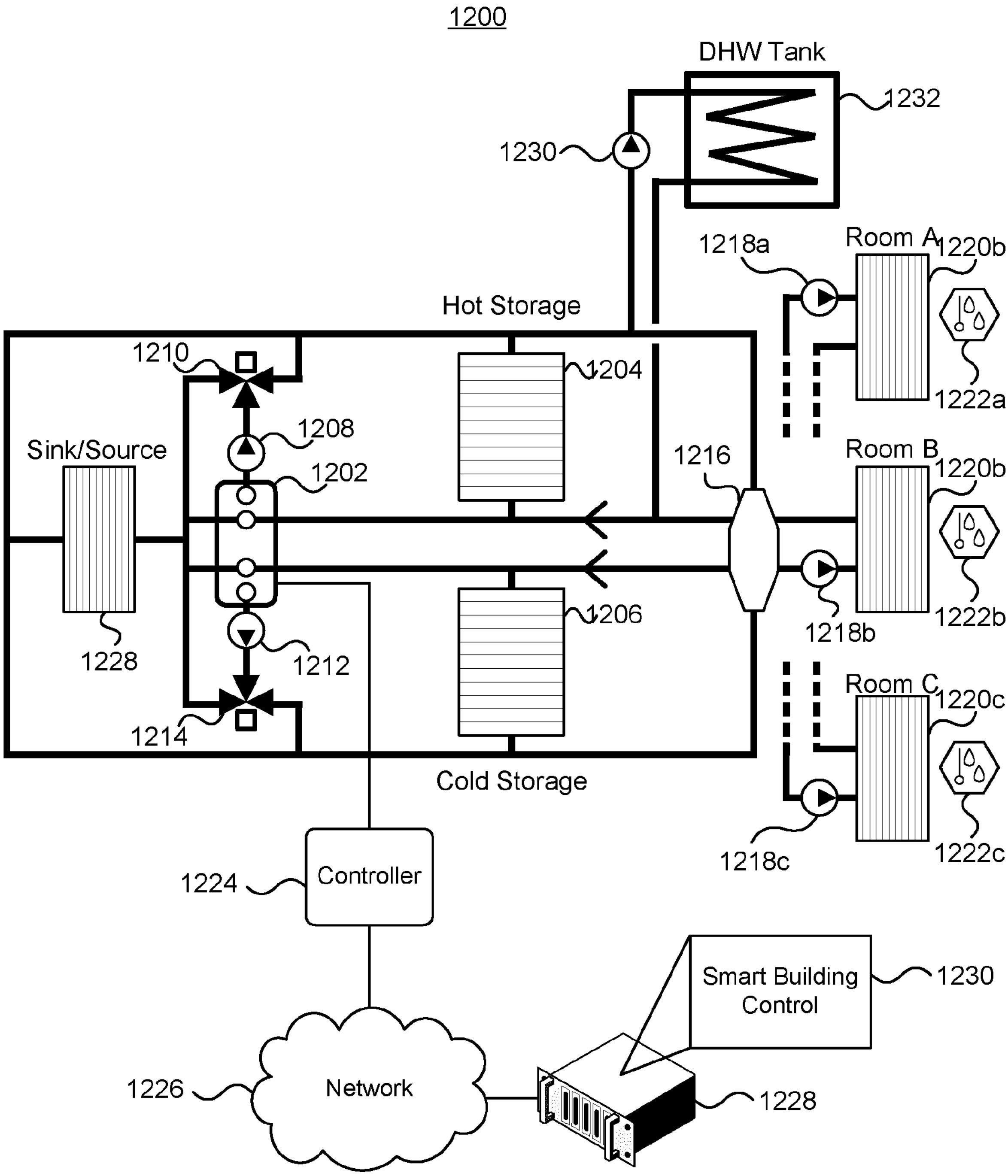
1200
DHW Tank
1232
1230
1218a
Room A
1220b
Hot Storage
1210
1204
1208
Sink/Source
1202
1216
Room B
1220b
1222a
1206
1228
1212
1218b
1222b
Room C
1220c
1214
Cold Storage
1218c
1222c
1224
Controller
Smart Building
Control
1230
1226
Network
1228

FIG. 12

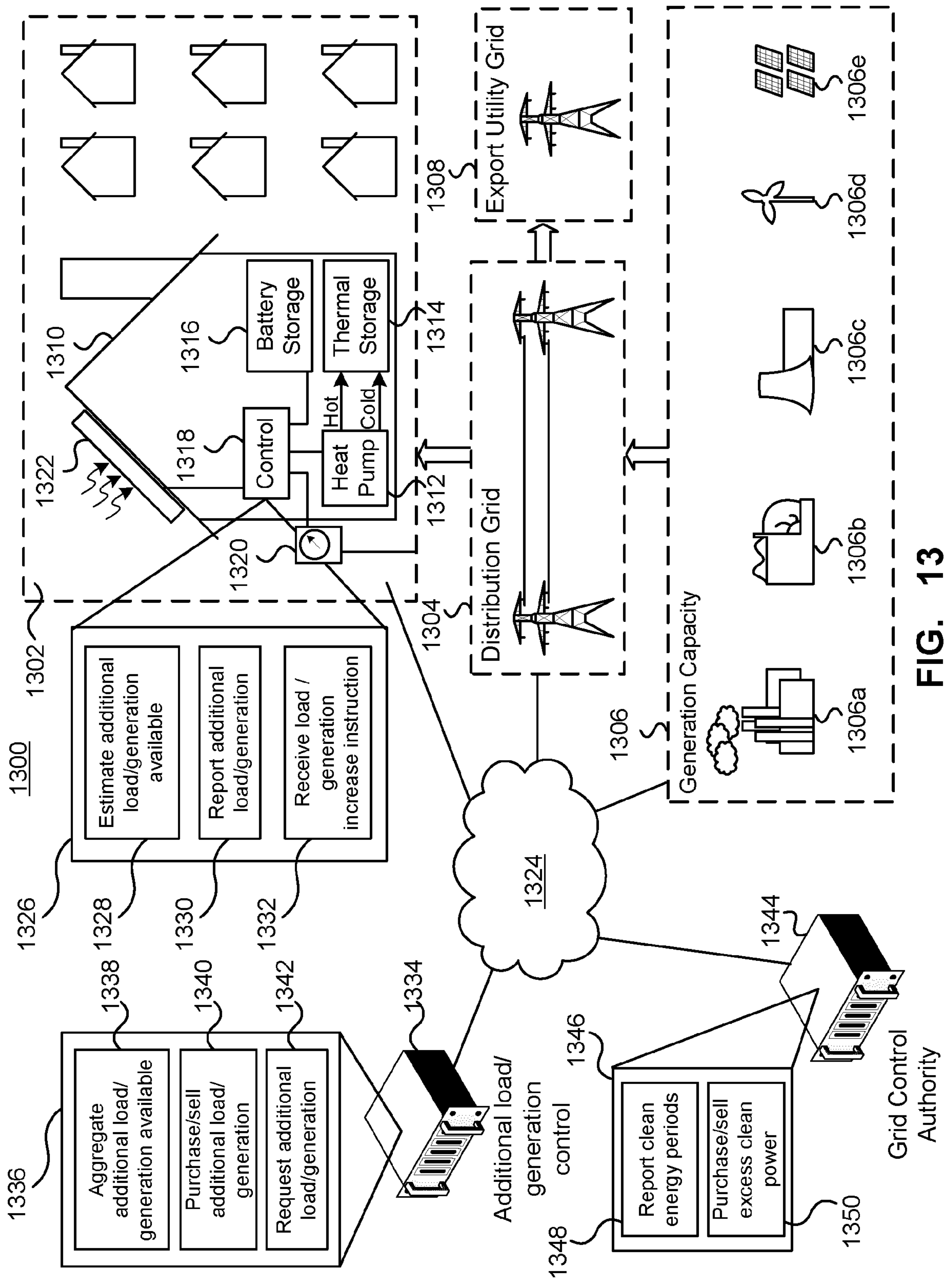
1300
1302
Export Utility Grid
1308
1310
1316
Battery Storage
Thermal Storage
1314
1322
1318
Control
Hot
Cold
Heat Pump
1312
1320
Distribution Grid
1304
Generation Capacity
1306
1306a
1306b
1306c
1306d
1306e
1326
Estimate additional load/generation available
1328
Report additional load/generation
1330
Receive load / generation increase instruction
1332
1324
1336
Aggregate additional load/ generation available
1338
Purchase/sell additional load/ generation
1340
Request additional load/generation
1342
1334
Additional load/ generation control
1344
1346
Report clean energy periods
1348
Purchase/sell excess clean power
1350
Grid Control Authority

FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2019/050545

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***F24F 5/00*** (2006.01) , ***F24D 11/02*** (2006.01) , ***F24D 3/12*** (2006.01) , ***F24F 12/00*** (2006.01) , ***F24F 13/30*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC (2006.01): F24F 5/00, F24D 11/02, F24D 3/12, F24F 12/00, F24F 13/30

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Internet (Google)
Questel (Orbit)
Keywords: radiant, hydronic, heat pump, energy efficient, hot storage vessel, thermal storage, thermal energy, battery, heating, cooling, stor+, controller, server, smart meter, power, thermal, additional, estimate+, grid, geothermal, apple, google, tesla

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO2015/021525A1 (GLOVER, M. et al.) 19 February 2015 (19-02-2015) *Figures 9-11 and 13; Page 3, line 3; Page 17, lines 4-6 and lines 26-29; Page 19, lines 22-27; Page 25, lines 4-6; Page 31, lines17-19; Page 32, lines18-22; Page 33, lines 9, 10, and 16-23; claim 1*	1-66, 97 and 99 67-96
Y	US2015/0167989A1 (MATSUOKA, Y. et al.) 18 June 2015 (18-06-2015) *Figures 3, 6, 10, 11 and 43; Paragraphs [0056], [0064] and [0071]-[0074]*	67-96
A	US2014/0277769A1 (MATSUOKA, Y. et al.) 18 September 2014 (18-09-2014) *abstract; Figures 1-32*	1-97 and 99

☐ Further documents are listed in the continuation of Box C.

☑ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier application or patent but published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search
03 July 2019 (03-07-2019)

Date of mailing of the international search report
08 July 2019 (08-07-2019)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C114 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 819-953-2476

Authorized officer

Branka Ristovski (819) 934-2578

Box No. II **Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claim Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III **Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

The independent claims are directed to a plurality of inventive concepts as listed in the Supplemental Box I.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☑ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos.:
1-97 and 99

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continuation of Box III:

The independent claims are directed to a plurality of inventive concepts as follows:
Group A: Claim 1 is directed to an energy efficient building HVAC system comprising a thermal energy storage system, an electric heat pump and a hydronic heating/cooling system;
Group B: Claim 44 is directed to a thermal storage system comprising a thermal energy storage, a non-reversing electric heat pump and a building controller that controls operation of the heat pump based on an indication that electricity supply is generated from non-fossil fuel sources;
Group C: Claims 67, 77 and 87 are directed to a building energy management system and a method of operating a heat pump, wherein the system includes a hydronic heating/cooling system, a thermal storage system, an electric heat pump, and a building controller configured to estimate an amount of additional thermal energy for storing, and for consumption by the electric heat pump, and a central server that determines the supply from non-fossil fuels and transmit the messages providing the indication to increase electricity consumption;
Group D: Claims 97 and 99 are directed to a system and a method of heating/cooling including steps of opening and closing a valve that regulates a flow of a heat transfer liquid to radiant hydronic panels;
Group E: Claim 98 is directed to a method of determining required heating/cooling based on room occupation and temperature sensor readings;
Group F: Claims 100 and 101 are directed to a displacement ventilation system and an enthalpy heat exchanger, wherein the system includes first and second gas-liquid heat exchangers including a tubing and a piping loop; and

Group **A** may be combined with any one of groups **B**, **C** and **D**.

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
WO2015021525A1	19 February 2015 (19-02-2015)	WO2015021525A8	16 April 2015 (16-04-2015)
		CA2881677A1	20 February 2014 (20-02-2014)
		CA2881677C	29 January 2019 (29-01-2019)
		EP2882920A1	17 June 2015 (17-06-2015)
		EP2882920A4	04 May 2016 (04-05-2016)
		EP2882920B1	28 November 2018 (28-11-2018)
		US2015219344A1	06 August 2015 (06-08-2015)
		US9897332B2	20 February 2018 (20-02-2018)
		US2010300645A1	02 December 2010 (02-12-2010)
		US2012318475A1	20 December 2012 (20-12-2012)
		US2018163976A1	14 June 2018 (14-06-2018)
		WO2014026268A1	20 February 2014 (20-02-2014)
US2015167989A1	18 June 2015 (18-06-2015)	None	
US2014277769A1	18 September 2014 (18-09-2014)	US2014277769A1	18 September 2014 (18-09-2014)
		US9595070B2	14 March 2017 (14-03-2017)
		AU2014237606A1	03 September 2015 (03-09-2015)
		AU2014239934A1	03 September 2015 (03-09-2015)
		AU2014239934B2	15 March 2018 (15-03-2018)
		AU2014254089A1	29 October 2015 (29-10-2015)
		AU2014254089B2	12 October 2017 (12-10-2017)
		AU2018200113A1	25 January 2018 (25-01-2018)
		AU2018200113B2	14 March 2019 (14-03-2019)
		AU2018203856A1	21 June 2018 (21-06-2018)
		AU2019201286A1	14 March 2019 (14-03-2019)
		CA2902183A1	25 September 2014 (25-09-2014)
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		CA2909797A1	23 October 2014 (23-10-2014)
		CN105210006A	30 December 2015 (30-12-2015)
		CN105210006B	06 November 2018 (06-11-2018)
		CN105283817A	27 January 2016 (27-01-2016)
		CN105283817B	15 March 2019 (15-03-2019)
		CN105378589A	02 March 2016 (02-03-2016)
		CN105378589B	06 November 2018 (06-11-2018)
		CN109461094A	12 March 2019 (12-03-2019)
		CN109582112A	05 April 2019 (05-04-2019)
		EP2972654A1	20 January 2016 (20-01-2016)
		EP2972654A4	01 February 2017 (01-02-2017)
		EP2972661A2	20 January 2016 (20-01-2016)
		EP2972661A4	09 November 2016 (09-11-2016)
		EP2987042A1	24 February 2016 (24-02-2016)
		EP2987042A4	28 December 2016 (28-12-2016)
		JP2016519801A	07 July 2016 (07-07-2016)
		JP6396985B2	26 September 2018 (26-09-2018)
		JP2016521343A	21 July 2016 (21-07-2016)
		JP6457491B2	23 January 2019 (23-01-2019)
		JP2016522467A	28 July 2016 (28-07-2016)
		JP2019071086A	09 May 2019 (09-05-2019)
		JP2019071086A	09 May 2019 (09-05-2019)
		KR20150131341A	24 November 2015 (24-11-2015)
		KR20150131343A	24 November 2015 (24-11-2015)
		KR20160002993A	08 January 2016 (08-01-2016)

US2014277795A1	18 September 2014 (18-09-2014)
US9807099B2	31 October 2017 (31-10-2017)
US2014277761A1	18 September 2014 (18-09-2014)
US9810442B2	07 November 2017 (07-11-2017)
US2016373453A1	22 December 2016 (22-12-2016)
US9998475B2	12 June 2018 (12-06-2018)
US2017241663A1	24 August 2017 (24-08-2017)
US2018069868A1	08 March 2018 (08-03-2018)
US2018088605A1	29 March 2018 (29-03-2018)
US2018302411A1	18 October 2018 (18-10-2018)
WO2014149993A1	25 September 2014 (25-09-2014)
WO2014152301A2	25 September 2014 (25-09-2014)
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WO2014172374A1	23 October 2014 (23-10-2014)