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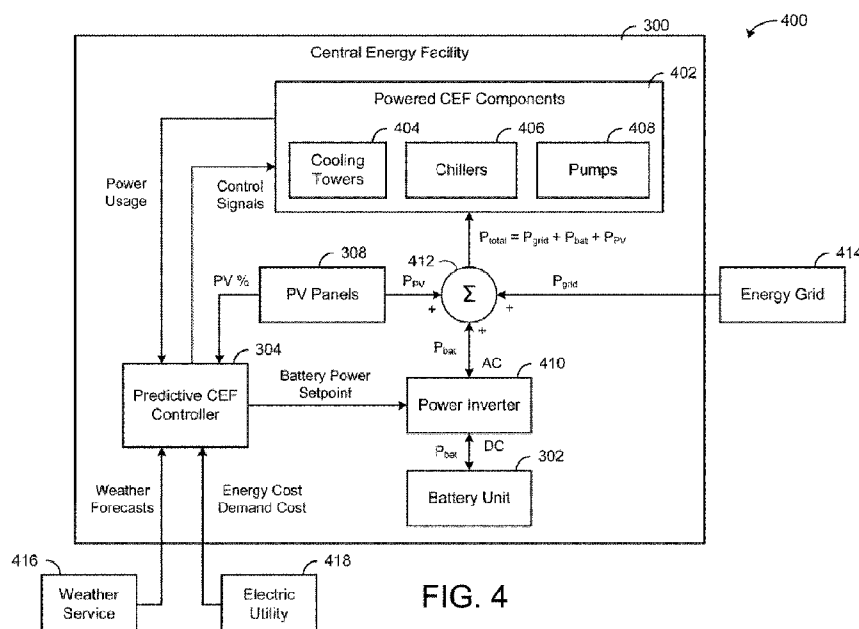


FIG. 4

(57) Abstract: A central energy facility (CEF) includes a plurality of powered CEF components, a battery unit, and a predictive CEF controller. The powered CEF components include a chiller unit and a cooling tower. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered CEF components. The predictive CEF controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered CEF components at each time step of an optimization period.



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BUILDING EQUIPMENT WITH PREDICTIVE CONTROL

CROSS-REFERENCE TO RELATED PATENT APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 62/524,325 filed June 23, 2017, the entire disclosure of which is incorporated by reference herein.

BACKGROUND

[0002] The present disclosure relates generally to building equipment with predictive control and more particularly to HVAC equipment such as chillers, boilers, cooling towers, valves, pumps, and other types of equipment for use in a central energy facility or building HVAC system.

[0003] A central energy facility (CEF) includes various types of HVAC equipment configured to provide heating or cooling for a building. For example, a CEF may include chillers, boilers, heat recovery chillers, cooling towers, valves, pumps, actuators, and other type of equipment configured to heat or cool a working fluid circulated to a building. The heated or cooled fluid can be provided to an air handling unit or rooftop unit in order to exchange heat with an airflow provided to one or more zones of the building.

[0004] The equipment of a CEF may include several components that consume power during operation. For example, a chiller may include a compressor configured to circulate a refrigerant through a refrigeration circuit. A cooling tower may include one or more fans configured to facilitate airflow through the cooling tower. Valve, actuators, and pumps may also consume power during operation. It would be desirable to minimize the power consumption of these and other power-consuming components in order to reduce the cost of energy consumed by the CEF.

SUMMARY

[0005] One implementation of the present disclosure is a central energy facility (CEF). The CEF includes a plurality of powered CEF components, a battery unit, and a predictive CEF controller. The powered CEF components include a chiller unit and a cooling tower. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered CEF components. The predictive

CEF controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered CEF components at each time step of an optimization period.

[0006] In some embodiments, the CEF includes one or more photovoltaic panels configured to collect photovoltaic energy. The predictive CEF controller may be configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered CEF components at each time step of the optimization period.

[0007] In some embodiments, the predictive cost function accounts for a cost of the electric energy purchased from the energy grid at each time step of the optimization period and a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

[0008] In some embodiments, the predictive CEF controller is configured to receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period and use the energy pricing data as inputs to the predictive cost function.

[0009] In some embodiments, the predictive cost function accounts for a demand charge based on a maximum power consumption of the CEF during a demand charge period that overlaps at least partially with the optimization period. The predictive CEF controller may be configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

[0010] In some embodiments, the predictive CEF controller includes an economic controller configured to determine optimal power setpoints for the powered CEF components and for the battery unit at each time step of the optimization period, a tracking controller configured to use the optimal power setpoints to determine optimal temperature setpoints at each time step of the optimization period, and an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered CEF components and for the battery unit at each time step of the optimization period.

[0011] Another implementation of the present disclosure is an air-cooled chiller unit. The air-cooled chiller unit includes a refrigeration circuit, a plurality of powered chiller

components, a battery unit, and a predictive chiller controller. The refrigeration circuit includes an evaporator and a condenser. The powered chiller components include a compressor configured to circulate a refrigerant through the refrigeration circuit and a fan configured to provide cooling for the condenser. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered chiller components. The predictive chiller controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered chiller components at each time step of an optimization period

[0012] In some embodiments, the air-cooled chiller unit includes one or more photovoltaic panels configured to collect photovoltaic energy. The predictive chiller controller may be configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered chiller components at each time step of the optimization period.

[0013] In some embodiments, the predictive cost function accounts for a cost of the electric energy purchased from the energy grid at each time step of the optimization period and a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

[0014] In some embodiments, the predictive chiller controller is configured to receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period and use the energy pricing data as inputs to the predictive cost function.

[0015] In some embodiments, the predictive cost function accounts for a demand charge based on a maximum power consumption of the air-cooled chiller unit during a demand charge period that overlaps at least partially with the optimization period. The predictive chiller controller may be configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

[0016] In some embodiments, the predictive chiller controller includes an economic controller configured to determine optimal power setpoints for the powered chiller components and for the battery unit at each time step of the optimization period, a tracking controller configured to use the optimal power setpoints to determine optimal temperature

setpoints at each time step of the optimization period, and an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered chiller components and for the battery unit at each time step of the optimization period.

[0017] Another implementation of the present disclosure is a pump unit. The pump unit includes a pump, a battery unit, and a predictive pump controller. The pump is configured to circulate a fluid through a fluid circuit. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the pump. The predictive pump controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the pump at each time step of an optimization period.

[0018] In some embodiments, the predictive cost function accounts for a cost of the electric energy purchased from the energy grid at each time step of the optimization period and a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

[0019] In some embodiments, the predictive pump controller is configured to receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period and use the energy pricing data as inputs to the predictive cost function.

[0020] In some embodiments, the predictive cost function accounts for a demand charge based on a maximum power consumption of the pump unit during a demand charge period that overlaps at least partially with the optimization period. The predictive pump controller may be configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

[0021] In some embodiments, the predictive pump controller includes an economic controller configured to determine optimal power setpoints for the pump and for the battery unit at each time step of the optimization period, a tracking controller configured to use the optimal power setpoints to determine optimal flow setpoints or pressure setpoints at each time step of the optimization period, and an equipment controller configured to use the optimal flow setpoints or pressure setpoints to generate control signals for the pump and for the battery unit at each time step of the optimization period.

[0022] Another implementation of the present disclosure is a cooling tower unit. The cooling tower unit includes one or more powered cooling tower components, a battery unit, and a predictive cooling tower controller. The cooling tower components include at least one of a fan and a pump. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered cooling tower components. The predictive cooling tower controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered cooling tower components at each time step of an optimization period.

[0023] In some embodiments, the cooling tower unit includes one or more photovoltaic panels configured to collect photovoltaic energy. The predictive cooling tower controller may be configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered cooling tower components at each time step of the optimization period.

[0024] In some embodiments, the predictive cost function accounts for a cost of the electric energy purchased from the energy grid at each time step of the optimization period and a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

[0025] In some embodiments, the predictive cooling tower controller is configured to receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period and use the energy pricing data as inputs to the predictive cost function.

[0026] In some embodiments, the predictive cost function accounts for a demand charge based on a maximum power consumption of the cooling tower unit during a demand charge period that overlaps at least partially with the optimization period. The predictive cooling tower controller may be configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

[0027] In some embodiments, the predictive cooling tower controller includes an economic controller configured to determine optimal power setpoints for the powered cooling tower components and for the battery unit at each time step of the optimization period, a tracking controller configured to use the optimal power setpoints to determine optimal temperature

setpoints at each time step of the optimization period, and an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered cooling tower components and for the battery unit at each time step of the optimization period.

[0028] Another implementation of the present disclosure is a valve unit. The valve unit includes a valve, one or more powered valve components, a battery unit, and a predictive valve controller. The valve is configured to control a flowrate of a fluid through a fluid conduit. The powered valve components include a valve actuator coupled to the valve and configured to modulate a position of the valve. The battery unit is configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered valve components. The predictive valve controller is configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered valve components at each time step of an optimization period.

[0029] In some embodiments, the predictive cost function accounts for a cost of the electric energy purchased from the energy grid at each time step of the optimization period and a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

[0030] In some embodiments, the predictive valve controller is configured to receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period and use the energy pricing data as inputs to the predictive cost function.

[0031] In some embodiments, the predictive cost function accounts for a demand charge based on a maximum power consumption of the valve unit during a demand charge period that overlaps at least partially with the optimization period. The predictive valve controller may be configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

[0032] In some embodiments, the predictive valve controller includes an economic controller configured to determine optimal power setpoints for the powered valve components and for the battery unit at each time step of the optimization period, a tracking controller configured to use the optimal power setpoints to determine optimal position setpoints at each time step of the optimization period, and an equipment controller configured

to use the optimal temperature setpoints to generate control signals for the powered valve components and for the battery unit at each time step of the optimization period.

[0033] Those skilled in the art will appreciate that the summary is illustrative only and is not intended to be in any way limiting. Other aspects, inventive features, and advantages of the devices and/or processes described herein, as defined solely by the claims, will become apparent in the detailed description set forth herein and taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] FIG. 1 is a drawing of a building equipped with a HVAC system, according to some embodiments.

[0035] FIG. 2 is a drawing of a central energy facility (CEF) which can be used to provide heating or cooling to the building of FIG. 1, according to some embodiments.

[0036] FIG. 3 is a drawing of a CEF with a battery unit and a predictive CEF controller, according to some embodiments.

[0037] FIG. 4 is a block diagram of a predictive CEF control system including the battery unit and predictive CEF controller of FIG. 3, according to some embodiments.

[0038] FIG. 5 is a block diagram illustrating the predictive CEF controller of FIG. 3 in greater detail, according to some embodiments.

[0039] FIG. 6 is a graph of a user interface which can be generated by the predictive CEF controller of FIG. 3, according to some embodiments.

[0040] FIG. 7 is a drawing of an air-cooled chiller unit with a battery unit and a predictive chiller controller, according to some embodiments.

[0041] FIG. 8 is a block diagram of the air-cooled chiller unit of FIG. 7, according to some embodiments.

[0042] FIG. 9 is a block diagram of a predictive chiller control system including the battery unit and predictive chiller controller of FIG. 7, according to some embodiments.

[0043] FIG. 10 is a block diagram illustrating the predictive chiller controller of FIG. 7 in greater detail, according to some embodiments.

[0044] FIG. 11 is a drawing of a pump unit with a battery unit and a predictive pump controller, according to some embodiments.

[0045] FIG. 12 is a block diagram of the pump unit of FIG. 11, according to some embodiments.

[0046] FIG. 13 is a block diagram of a predictive pump control system including the battery unit and predictive pump controller of FIG. 11, according to some embodiments.

[0047] FIG. 14 is a block diagram illustrating the predictive pump controller of FIG. 11 in greater detail, according to some embodiments.

[0048] FIG. 15 is a drawing of a cooling tower unit with a battery unit and a predictive cooling tower controller, according to some embodiments.

[0049] FIG. 16 is a block diagram of a predictive cooling tower control system including the battery unit and predictive cooling tower controller of FIG. 15, according to some embodiments.

[0050] FIG. 17 is a block diagram illustrating the predictive cooling tower controller of FIG. 15 in greater detail, according to some embodiments.

[0051] FIG. 18 is a drawing of a valve unit with a battery unit and a predictive valve controller, according to some embodiments.

[0052] FIG. 19 is a block diagram of the valve unit of FIG. 18, according to some embodiments.

[0053] FIG. 20 is a block diagram of a predictive valve control system including the battery unit and predictive valve controller of FIG. 18, according to some embodiments.

[0054] FIG. 21 is a block diagram illustrating the predictive valve controller of FIG. 18 in greater detail, according to some embodiments.

DETAILED DESCRIPTION

Building and HVAC System

[0055] Referring now to FIG. 1, a perspective view of a building 10 is shown. Building 10 is served by a BMS. A BMS is, in general, a system of devices configured to control, monitor, and manage equipment in or around a building or building area. A BMS can include, for example, a HVAC system, a security system, a lighting system, a fire alerting

system, any other system that is capable of managing building functions or devices, or any combination thereof.

[0056] The BMS that serves building 10 includes a HVAC system 100. HVAC system 100 can include a plurality of HVAC devices (e.g., heaters, chillers, air handling units, pumps, fans, thermal energy storage, etc.) configured to provide heating, cooling, ventilation, or other services for building 10. For example, HVAC system 100 is shown to include a waterside system 120 and an airside system 130. Waterside system 120 may provide a heated or chilled fluid to an air handling unit of airside system 130. Airside system 130 may use the heated or chilled fluid to heat or cool an airflow provided to building 10.

[0057] HVAC system 100 is shown to include a chiller 102, a boiler 104, and a rooftop air handling unit (AHU) 106. Waterside system 120 may use boiler 104 and chiller 102 to heat or cool a working fluid (e.g., water, glycol, etc.) and may circulate the working fluid to AHU 106. In various embodiments, the HVAC devices of waterside system 120 can be located in or around building 10 (as shown in FIG. 1) or at an offsite location such as a central plant (e.g., a chiller plant, a steam plant, a heat plant, etc.). The working fluid can be heated in boiler 104 or cooled in chiller 102, depending on whether heating or cooling is required in building 10. Boiler 104 may add heat to the circulated fluid, for example, by burning a combustible material (e.g., natural gas) or using an electric heating element. Chiller 102 may place the circulated fluid in a heat exchange relationship with another fluid (e.g., a refrigerant) in a heat exchanger (e.g., an evaporator) to absorb heat from the circulated fluid. The working fluid from chiller 102 and/or boiler 104 can be transported to AHU 106 via piping 108.

[0058] AHU 106 may place the working fluid in a heat exchange relationship with an airflow passing through AHU 106 (e.g., via one or more stages of cooling coils and/or heating coils). The airflow can be, for example, outside air, return air from within building 10, or a combination of both. AHU 106 may transfer heat between the airflow and the working fluid to provide heating or cooling for the airflow. For example, AHU 106 can include one or more fans or blowers configured to pass the airflow over or through a heat exchanger containing the working fluid. The working fluid may then return to chiller 102 or boiler 104 via piping 110.

[0059] Airside system 130 may deliver the airflow supplied by AHU 106 (i.e., the supply airflow) to building 10 via air supply ducts 112 and may provide return air from building 10

to AHU 106 via air return ducts 114. In some embodiments, airside system 130 includes multiple variable air volume (VAV) units 116. For example, airside system 130 is shown to include a separate VAV unit 116 on each floor or zone of building 10. VAV units 116 can include dampers or other flow control elements that can be operated to control an amount of the supply airflow provided to individual zones of building 10. In other embodiments, airside system 130 delivers the supply airflow into one or more zones of building 10 (e.g., via supply ducts 112) without using intermediate VAV units 116 or other flow control elements. AHU 106 can include various sensors (e.g., temperature sensors, pressure sensors, etc.) configured to measure attributes of the supply airflow. AHU 106 may receive input from sensors located within AHU 106 and/or within the building zone and may adjust the flow rate, temperature, or other attributes of the supply airflow through AHU 106 to achieve setpoint conditions for the building zone.

Central Energy Facility

[0060] Referring now to FIG. 2, a block diagram of a central energy facility (CEF) 200 is shown, according to some embodiments. In various embodiments, CEF 200 may supplement or replace waterside system 120 in HVAC system 100 or can be implemented separate from HVAC system 100. When implemented in HVAC system 100, CEF 200 can include a subset of the HVAC devices in HVAC system 100 (e.g., boiler 104, chiller 102, pumps, valves, etc.) and may operate to supply a heated or chilled fluid to AHU 106. The HVAC devices of CEF 200 can be located within building 10 (e.g., as components of waterside system 120) or at an offsite location.

[0061] CEF 200 is shown to include a plurality of subplants 202-212 including a heater subplant 202, a heat recovery chiller subplant 204, a chiller subplant 206, a cooling tower subplant 208, a hot thermal energy storage (TES) subplant 210, and a cold thermal energy storage (TES) subplant 212. Subplants 202-212 consume resources (e.g., water, natural gas, electricity, etc.) from utilities to serve thermal energy loads (e.g., hot water, cold water, heating, cooling, etc.) of a building or campus. For example, heater subplant 202 can be configured to heat water in a hot water loop 214 that circulates the hot water between heater subplant 202 and building 10. Chiller subplant 206 can be configured to chill water in a cold water loop 216 that circulates the cold water between chiller subplant 206 building 10. Heat recovery chiller subplant 204 can be configured to transfer heat from cold water loop 216 to hot water loop 214 to provide additional heating for the hot water and additional cooling for

the cold water. Condenser water loop 218 may absorb heat from the cold water in chiller subplant 206 and reject the absorbed heat in cooling tower subplant 208 or transfer the absorbed heat to hot water loop 214. Hot TES subplant 210 and cold TES subplant 212 may store hot and cold thermal energy, respectively, for subsequent use.

[0062] Hot water loop 214 and cold water loop 216 may deliver the heated and/or chilled water to air handlers located on the rooftop of building 10 (e.g., AHU 106) or to individual floors or zones of building 10 (e.g., VAV units 116). The air handlers push air past heat exchangers (e.g., heating coils or cooling coils) through which the water flows to provide heating or cooling for the air. The heated or cooled air can be delivered to individual zones of building 10 to serve thermal energy loads of building 10. The water then returns to subplants 202-212 to receive further heating or cooling.

[0063] Although subplants 202-212 are shown and described as heating and cooling water for circulation to a building, it is understood that any other type of working fluid (e.g., glycol, CO₂, etc.) can be used in place of or in addition to water to serve thermal energy loads. In other embodiments, subplants 202-212 may provide heating and/or cooling directly to the building or campus without requiring an intermediate heat transfer fluid. These and other variations to CEF 200 are within the teachings of the present disclosure.

[0064] Each of subplants 202-212 can include a variety of equipment configured to facilitate the functions of the subplant. For example, heater subplant 202 is shown to include a plurality of heating elements 220 (e.g., boilers, electric heaters, etc.) configured to add heat to the hot water in hot water loop 214. Heater subplant 202 is also shown to include several pumps 222 and 224 configured to circulate the hot water in hot water loop 214 and to control the flow rate of the hot water through individual heating elements 220. Chiller subplant 206 is shown to include a plurality of chillers 232 configured to remove heat from the cold water in cold water loop 216. Chiller subplant 206 is also shown to include several pumps 234 and 236 configured to circulate the cold water in cold water loop 216 and to control the flow rate of the cold water through individual chillers 232.

[0065] Heat recovery chiller subplant 204 is shown to include a plurality of heat recovery heat exchangers 226 (e.g., refrigeration circuits) configured to transfer heat from cold water loop 216 to hot water loop 214. Heat recovery chiller subplant 204 is also shown to include several pumps 228 and 230 configured to circulate the hot water and/or cold water through heat recovery heat exchangers 226 and to control the flow rate of the water through

individual heat recovery heat exchangers 226. Cooling tower subplant 208 is shown to include a plurality of cooling towers 238 configured to remove heat from the condenser water in condenser water loop 218. Cooling tower subplant 208 is also shown to include several pumps 240 configured to circulate the condenser water in condenser water loop 218 and to control the flow rate of the condenser water through individual cooling towers 238.

[0066] Hot TES subplant 210 is shown to include a hot TES tank 242 configured to store the hot water for later use. Hot TES subplant 210 may also include one or more pumps or valves configured to control the flow rate of the hot water into or out of hot TES tank 242. Cold TES subplant 212 is shown to include cold TES tanks 244 configured to store the cold water for later use. Cold TES subplant 212 may also include one or more pumps or valves configured to control the flow rate of the cold water into or out of cold TES tanks 244.

[0067] In some embodiments, one or more of the pumps in CEF 200 (e.g., pumps 222, 224, 228, 230, 234, 236, and/or 240) or pipelines in CEF 200 include an isolation valve associated therewith. Isolation valves can be integrated with the pumps or positioned upstream or downstream of the pumps to control the fluid flows in CEF 200. In various embodiments, CEF 200 can include more, fewer, or different types of devices and/or subplants based on the particular configuration of CEF 200 and the types of loads served by CEF 200.

Central Energy Facility With Battery Unit and Predictive Control

[0068] Referring now to FIG. 3, a central energy facility (CEF) 300 with a battery unit 302 and predictive CEF controller 304 is shown, according to some embodiments. CEF 300 can be configured to provide cooling to a cooling load 322. Cooling load 322 can include, for example, a building zone, a supply airstream flowing through an air duct, an airflow in an air handling unit or rooftop unit, fluid flowing through a heat exchanger, a refrigerator or freezer, a condenser or evaporator, a cooling coil, or any other type of system, device, or space which requires cooling. In some embodiments, a pump 318 circulates a chilled fluid to cooling load 322 via a chilled fluid circuit 336. The chilled fluid can absorb heat from cooling load 322, thereby providing cooling to cooling load 322 and warming the chilled fluid.

[0069] CEF 300 is shown to include a cooling tower 312 and a chiller 320. Cooling tower 312 can be configured to cool the water in cooling tower circuit 332 by transferring heat from the water to outside air. In some embodiments, a pump 316 circulates water through cooling tower 312 via cooling tower circuit 332. Cooling tower 312 may include a fan 314 which causes cool air to flow through cooling tower 312. Cooling tower 312 places the cool air in a

heat exchange relationship with the warmer water, thereby transferring heat from warmer water to the cooler air. Cooling tower 312 can provide cooling for a condenser 326 of chiller 320. Condenser 326 can transfer heat from the refrigerant in refrigeration circuit 334 to the water in cooling tower circuit 332. Although cooling tower circuit 332 is shown and described as circulating water, it should be understood that any type of coolant or working fluid (e.g., water, glycol, CO₂, etc.) can be used in cooling tower circuit 332.

[0070] Chiller 320 is shown to include a condenser 326, a compressor 328, an evaporator 330, and an expansion device 324. Compressor 328 can be configured to circulate a refrigerant between condenser 326 and evaporator 330 via refrigeration circuit 334. Compressor 328 operates to compress the refrigerant to a high pressure, high temperature state. The compressed refrigerant flows through condenser 326, which transfers heat from the refrigerant in refrigeration circuit 334 to the water in cooling tower circuit 332. The cooled refrigerant then flows through expansion device 324, which expands the refrigerant to a low temperature, low pressure state. The expanded refrigerant flows through evaporator 330, which transfers heat from the chilled fluid in chilled fluid circuit 336 to the refrigerant in refrigeration circuit 334.

[0071] In some embodiments, CEF 300 includes multiple chillers 320. Each of chillers 320 can be arranged in parallel and configured to provide cooling for the fluid in chilled fluid circuit 336. The set of chillers 320 may have a cooling capacity of approximately 1-3 MW or 1000-6000 tons in some embodiments. Similarly, CEF 300 can include multiple cooling towers 312. Each of the cooling towers 312 can be arranged in parallel and configured to provide cooling for the water in cooling tower circuit 332. Although only cooling components are shown in FIG. 3, it is contemplated that CEF 300 can include heating components in some embodiments. For example, CEF 300 may include one or more boilers, heat recovery chillers, steam generators, or other devices configured to provide heating. In some embodiments, CEF 300 includes some or all of the components of CEF 200, as described with reference to FIG. 2.

[0072] Still referring to FIG. 3, CEF 300 is shown to include a battery unit 302. In some embodiments, battery unit 302 includes one or more photovoltaic (PV) panels 308. PV panels 308 may include a collection of photovoltaic cells. The photovoltaic cells are configured to convert solar energy (i.e., sunlight) into electricity using a photovoltaic material such as monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium

telluride, copper indium gallium selenide/sulfide, or other materials that exhibit the photovoltaic effect. In some embodiments, the photovoltaic cells are contained within packaged assemblies that form PV panels 308. Each PV panel 308 may include a plurality of linked photovoltaic cells. PV panels 308 may combine to form a photovoltaic array.

[0073] In some embodiments, PV panels 308 are configured to maximize solar energy collection. For example, battery unit 302 may include a solar tracker (e.g., a GPS tracker, a sunlight sensor, etc.) that adjusts the angle of PV panels 308 so that PV panels 308 are aimed directly at the sun throughout the day. The solar tracker may allow PV panels 308 to receive direct sunlight for a greater portion of the day and may increase the total amount of power produced by PV panels 308. In some embodiments, battery unit 302 includes a collection of mirrors, lenses, or solar concentrators configured to direct and/or concentrate sunlight on PV panels 308. The energy generated by PV panels 308 may be stored in battery cells 306 and/or used to power various components of CEF 300.

[0074] In some embodiments, battery unit 302 includes one or more battery cells 306. Battery cells 306 are configured to store and discharge electric energy (i.e., electricity). In some embodiments, battery unit 302 is charged using electricity from an external energy grid (e.g., provided by an electric utility). The electricity stored in battery unit 302 can be discharged to power one or more powered components of CEF 300 (e.g., cooling tower 312, fan 314, chiller 320, pumps 316-318, etc.). Advantageously, battery unit 302 allows CEF 300 to draw electricity from the energy grid and charge battery unit 302 when energy prices are low and discharge the stored electricity when energy prices are high to time-shift the electric load of CEF 300. In some embodiments, battery unit 302 has sufficient energy capacity (e.g., 6-12 MW-hours) to power CEF 300 for approximately 4-6 hours when operating at maximum capacity such that battery unit 302 can be utilized during high energy cost periods and charged during low energy cost periods.

[0075] In some embodiments, predictive CEF controller 304 performs an optimization process to determine whether to charge or discharge battery unit 302 during each of a plurality of time steps that occur during an optimization period. Predictive CEF controller 304 may use weather and pricing data 310 to predict the amount of heating/cooling required and the cost of electricity during each of the plurality of time steps. Predictive CEF controller 304 can optimize an objective function that accounts for the cost of electricity purchased from the energy grid over the duration of the optimization period. In some

embodiments, the objective function also accounts for the cost of operating various components of CEF 300 (e.g., cost of natural gas used to fuel boilers). Predictive CEF controller 304 can determine an amount of electricity to purchase from the energy grid and an amount of electricity to store or discharge from battery unit 302 during each time step. The objective function and the optimization performed by predictive CEF controller 304 are described in greater detail with reference to FIGS. 4-5.

Predictive CEF Control System

[0076] Referring now to FIG. 4, a block diagram of a predictive CEF control system 400 is shown, according to some embodiments. Several of the components shown in control system 400 may be part of CEF 300. For example, CEF 300 may include powered CEF components 402, battery unit 302, predictive CEF controller 304, power inverter 410, and a power junction 412. Powered CEF components 402 may include any component of CEF 300 that consumes power (e.g., electricity) during operation. For example, powered CEF components 402 are shown to include cooling towers 404, chillers 406, and pumps 408. These components may be similar to cooling tower 312, chiller 320, and pumps 316-318, as described with reference to FIG. 3.

[0077] Power inverter 410 may be configured to convert electric power between direct current (DC) and alternating current (AC). For example, battery unit 302 may be configured to store and output DC power, whereas energy grid 414 and powered CEF components 402 may be configured to consume and provide AC power. Power inverter 410 may be used to convert DC power from battery unit 302 into a sinusoidal AC output synchronized to the grid frequency of energy grid 414 and/or powered CEF components 402. Power inverter 410 may also be used to convert AC power from energy grid 414 into DC power that can be stored in battery unit 302. The power output of battery unit 302 is shown as P_{bat} . P_{bat} may be positive if battery unit 302 is providing power to power inverter 410 (i.e., battery unit 302 is discharging) or negative if battery unit 302 is receiving power from power inverter 410 (i.e., battery unit 302 is charging).

[0078] In some instances, power inverter 410 receives a DC power output from battery unit 302 and converts the DC power output to an AC power output that can be provided to powered CEF components 402. Power inverter 410 may synchronize the frequency of the AC power output with that of energy grid 414 (e.g., 50 Hz or 60 Hz) using a local oscillator and may limit the voltage of the AC power output to no higher than the grid voltage. In some

embodiments, power inverter 410 is a resonant inverter that includes or uses LC circuits to remove the harmonics from a simple square wave in order to achieve a sine wave matching the frequency of energy grid 414. In various embodiments, power inverter 410 may operate using high-frequency transformers, low-frequency transformers, or without transformers. Low-frequency transformers may convert the DC output from battery unit 302 directly to the AC output provided to powered CEF components 402. High-frequency transformers may employ a multi-step process that involves converting the DC output to high-frequency AC, then back to DC, and then finally to the AC output provided to powered CEF components 402.

[0079] The power output of PV panels 308 is shown as P_{PV} . The power output P_{PV} of PV panels 308 can be stored in battery unit 302 and/or used to power powered CEF components 402. In some embodiments, PV panels 308 measure the amount of power P_{PV} generated by PV panels 308 and provides an indication of the PV power to predictive CEF controller 304. For example, PV panels 308 are shown providing an indication of the PV power percentage (i.e., PV %) to predictive CEF controller 304. The PV power percentage may represent a percentage of the maximum PV power at which PV panels 308 are currently operating.

[0080] Power junction 412 is the point at which powered CEF components 402, energy grid 414, PV panels 308, and power inverter 410 are electrically connected. The power supplied to power junction 412 from power inverter 410 is shown as P_{bat} . P_{bat} may be positive if power inverter 410 is providing power to power junction 412 (i.e., battery unit 302 is discharging) or negative if power inverter 410 is receiving power from power junction 412 (i.e., battery unit 302 is charging). The power supplied to power junction 412 from energy grid 414 is shown as P_{grid} and the power supplied to power junction 412 from PV panels 308 is shown as P_{PV} . P_{bat} , P_{PV} , and P_{grid} combine at power junction 412 to form P_{total} (i.e., $P_{total} = P_{grid} + P_{bat} + P_{PV}$). P_{total} may be defined as the power provided to powered CEF components 402 from power junction 412. In some instances, P_{total} is greater than P_{grid} . For example, when battery unit 302 is discharging, P_{bat} may be positive which adds to the grid power P_{grid} and the PV power P_{PV} when P_{bat} and P_{PV} combine with P_{grid} to form P_{total} . In other instances, P_{total} may be less than P_{grid} . For example, when battery unit 302 is charging, P_{bat} may be negative which subtracts from the grid power P_{grid} and the PV power P_{PV} when P_{bat} , P_{PV} , and P_{grid} combine to form P_{total} .

[0081] Predictive CEF controller 304 can be configured to control powered CEF components 402 and power inverter 410. In some embodiments, predictive CEF controller 304 generates and provides a battery power setpoint $P_{sp,bat}$ to power inverter 410. The battery power setpoint $P_{sp,bat}$ may include a positive or negative power value (e.g., kW) which causes power inverter 410 to charge battery unit 302 (when $P_{sp,bat}$ is negative) using power available at power junction 412 or discharge battery unit 302 (when $P_{sp,bat}$ is positive) to provide power to power junction 412 in order to achieve the battery power setpoint $P_{sp,bat}$.

[0082] In some embodiments, predictive CEF controller 304 generates and provides control signals to powered CEF components 402. Predictive CEF controller 304 may use a multi-stage optimization technique to generate the control signals. For example, predictive CEF controller 304 may include an economic controller configured to determine the optimal amount of power to be consumed by powered CEF components 402 at each time step during the optimization period. The optimal amount of power to be consumed may minimize a cost function that accounts for the cost of energy consumed by CEF 300. The cost of energy may be based on time-varying energy prices from electric utility 418. In some embodiments, predictive CEF controller 304 determines an optimal amount of power to purchase from energy grid 414 (i.e., a grid power setpoint $P_{sp,grid}$) and an optimal amount of power to store or discharge from battery unit 302 (i.e., a battery power setpoint $P_{sp,bat}$) at each of the plurality of time steps. Predictive CEF controller 304 may monitor the actual power usage of powered CEF components 402 and may utilize the actual power usage as a feedback signal when generating the optimal power setpoints.

[0083] Predictive CEF controller 304 may include a tracking controller configured to generate temperature setpoints (e.g., a zone temperature setpoint $T_{sp,zone}$, a chilled water temperature setpoint $T_{sp,chw}$, etc.) that achieve the optimal amount of power consumption at each time step. In some embodiments, predictive CEF controller 304 uses equipment models for powered CEF components 402 to determine an amount of heating or cooling that can be generated by CEF components 402 based on the optimal amount of power consumption. Predictive CEF controller 304 can use a zone temperature model in combination with weather forecasts from a weather service 416 to predict how the temperature of the building zone T_{zone} will change based on the power setpoints and/or the temperature setpoints.

[0084] In some embodiments, predictive CEF controller 304 uses the temperature setpoints to generate the control signals for powered CEF components 402. The control signals may

include on/off commands, speed setpoints for fans of cooling towers 404, power setpoints for compressors of chillers 406, chilled water temperature setpoints for chillers 406, pressure setpoints or flow rate setpoints for pumps 408, or other types of setpoints for individual devices of powered CEF components 402. In other embodiments, the control signals may include the temperature setpoints (e.g., a zone temperature setpoint $T_{sp,zone}$, a chilled water temperature setpoint $T_{sp,chw}$, etc.) generated by predictive CEF controller 304. The temperature setpoints can be provided to powered CEF components 402 or local controllers for powered CEF components 402 which operate to achieve the temperature setpoints. For example, a local controller for chillers 406 may receive a measurement of the chilled water temperature T_{chw} from chilled water temperature sensor and/or a measurement the zone temperature T_{zone} from a zone temperature sensor. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to increase or decrease the amount of cooling provided by chillers 406 to drive the measured temperature(s) to the temperature setpoint(s). Similar feedback control processes can be used to control cooling towers 404 and/or pumps 408. The multi-stage optimization performed by predictive CEF controller 304 is described in greater detail with reference to FIG. 5.

Predictive CEF Controller

[0085] Referring now to FIG. 5, a block diagram illustrating predictive CEF controller 304 in greater detail is shown, according to an exemplary embodiment. Predictive CEF controller 304 is shown to include a communications interface 502 and a processing circuit 504. Communications interface 502 may facilitate communications between controller 304 and external systems or devices. For example, communications interface 502 may receive measurements of the zone temperature T_{zone} from zone temperature sensor 516 and measurements of the power usage of powered CEF components 402. In some embodiments, communications interface 502 receives measurements of the state-of-charge (SOC) of battery unit 302, which can be provided as a percentage of the maximum battery capacity (i.e., battery %). Communications interface 502 can receive weather forecasts from a weather service 416 and predicted energy costs and demand costs from an electric utility 418. In some embodiments, predictive CEF controller 304 uses communications interface 502 to provide control signals powered CEF components 402 and power inverter 410.

[0086] Communications interface 502 may include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for

conducting data communications external systems or devices. In various embodiments, the communications may be direct (e.g., local wired or wireless communications) or via a communications network (e.g., a WAN, the Internet, a cellular network, etc.). For example, communications interface 502 can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, communications interface 502 can include a Wi-Fi transceiver for communicating via a wireless communications network or cellular or mobile phone communications transceivers.

[0087] Processing circuit 504 is shown to include a processor 506 and memory 508. Processor 506 may be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Processor 506 is configured to execute computer code or instructions stored in memory 508 or received from other computer readable media (e.g., CDROM, network storage, a remote server, etc.).

[0088] Memory 508 may include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory 508 may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory 508 may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. Memory 508 may be communicably connected to processor 506 via processing circuit 504 and may include computer code for executing (e.g., by processor 506) one or more processes described herein. When processor 506 executes instructions stored in memory 508 for completing the various activities described herein, processor 506 generally configures controller 304 (and more particularly processing circuit 504) to complete such activities.

[0089] Still referring to FIG. 5, predictive CEF controller 304 is shown to include an economic controller 510, a tracking controller 512, and an equipment controller 514. Controllers 510-514 can be configured to perform a multi-state optimization process to generate control signals for power inverter 410 and powered CEF components 402. In brief overview, economic controller 510 can optimize a predictive cost function to determine an

optimal amount of power to purchase from energy grid 414 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 302 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered CEF components 402 (i.e., a CEF power setpoint $P_{sp,total}$) at each time step of an optimization period. Tracking controller 512 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ to determine optimal temperature setpoints (e.g., a zone temperature setpoint $T_{sp,zone}$, a chilled water temperature setpoint $T_{sp,chw}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). Equipment controller 514 can use the optimal temperature setpoints $T_{sp,zone}$ or $T_{sp,chw}$ to generate control signals for powered CEF components 402 that drive the actual (e.g., measured) temperatures T_{zone} and/or T_{chw} to the setpoints (e.g., using a feedback control technique). Each of controllers 510-514 is described in detail below.

Economic Controller

[0090] Economic controller 510 can be configured to optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 414 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 302 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered CEF components 402 (i.e., a CEF power setpoint $P_{sp,total}$) at each time step of an optimization period. An example of a predictive cost function which can be optimized by economic controller 510 is shown in the following equation:

$$\begin{aligned} \min(J) = & \sum_{k=1}^h C_{ec}(k)P_{chiller}(k)\Delta t + \sum_{k=1}^h C_{ec}(k)P_{HRC}(k)\Delta t + \sum_{k=1}^h C_{gas}(k)F_{gas}(k)\Delta t \\ & + C_{DC} \max_k(P_{grid}(k)) - \sum_{k=1}^h C_{ec}(k)P_{bat}(k)\Delta t \end{aligned}$$

where $C_{ec}(k)$ is the cost per unit of electricity (e.g., \$/kWh) purchased from electric utility 418 during time step k , $P_{chiller}(k)$ is the power consumption (e.g., kW) of one or more chillers of CEF 300 during time step k , $P_{HRC}(k)$ is the power consumption of one or more heat recovery chillers (HRCs) of CEF 300 at time step k , $F_{gas}(k)$ is the natural gas consumption of one or more boilers of CEF 300 at time step k , $C_{gas}(k)$ is the cost per unit of natural gas consumed by CEF 300 at time step k , C_{DC} is the demand charge rate (e.g., \$/kW),

where the $\max(\cdot)$ term selects the maximum electricity purchase of CEF 300 (i.e., the maximum value of $P_{grid}(k)$) during any time step k of the optimization period, $P_{bat}(k)$ is the amount of power discharged from battery unit 302 during time step k , and Δt is the duration of each time step k . Economic controller 510 can optimize the predictive cost function J over the duration of the optimization period (e.g., from time step $k = 1$ to time step $k = h$) to predict the total cost of operating CEF 300 over the duration of the optimization period.

[0091] The first and second terms of the predictive cost function J represent the cost of electricity consumed by powered CEF components 402 over the duration of the optimization period. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 418. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variables $P_{chiller}(k)$ and $P_{HRC}(k)$ are decision variables which can be optimized by economic controller 510. In some embodiments, the total power consumption $P_{total}(k)$ of powered CEF components 402 at time step k is equal to the sum of $P_{chiller}(k)$ and $P_{HRC}(k)$ (i.e., $P_{total}(k) = P_{chiller}(k) + P_{HRC}(k)$). Accordingly, the first two terms of the predictive cost function can be replaced with the summation $\sum_{k=1}^h C_{ec}(k)P_{total}(k)\Delta t$ in some embodiments.

[0092] The third term of the predictive cost function J represents the cost of the fuel (e.g., natural gas) consumed by CEF 300 over the duration of the optimization period. The values of $C_{gas}(k)$ at each time step k can be defined by the energy cost information provided by a natural gas utility. In some embodiments, the cost of gas varies as a function of time, which results in different values of $C_{gas}(k)$ at different time steps k . The variable $F_{gas}(k)$ is a decision variable which can be optimized by economic controller 510.

[0093] The fourth term of the predictive cost function J represents the demand charge. Demand charge is an additional charge imposed by some utility providers based on the maximum power consumption during an applicable demand charge period. For example, the demand charge rate C_{DC} may be specified in terms of dollars per unit of power (e.g., \$/kW) and may be multiplied by the peak power usage (e.g., kW) during a demand charge period to calculate the demand charge. In the predictive cost function J , the demand charge rate C_{DC} may be defined by the demand cost information received from electric utility 418. The variable $P_{grid}(k)$ is a decision variable which can be optimized by economic controller 510 in order to reduce the peak power usage $\max(P_{grid}(k))$ that occurs during the demand charge

period. Load shifting may allow economic controller 510 to smooth momentary spikes in the electric demand of CEF 300 by storing energy in battery unit 302 when the power consumption of powered CEF components 402 is low. The stored energy can be discharged from battery unit 302 when the power consumption of powered CEF components 402 is high in order to reduce the peak power draw P_{grid} from energy grid 414, thereby decreasing the demand charge incurred.

[0094] The final term of the predictive cost function J represents the cost savings resulting from the use of battery unit 302. Unlike the previous terms in the cost function J , the final term subtracts from the total cost. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 418. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{bat}(k)$ is a decision variable which can be optimized by economic controller 510. A positive value of $P_{bat}(k)$ indicates that battery unit 302 is discharging, whereas a negative value of $P_{bat}(k)$ indicates that battery unit 302 is charging. The power discharged from battery unit 302 $P_{bat}(k)$ can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered CEF components 402, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 414 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). However, charging battery unit 302 results in a negative value of $P_{bat}(k)$ which adds to the total amount of power $P_{grid}(k)$ purchased from energy grid 414.

[0095] In some embodiments, the power P_{PV} provided by PV panels 308 is not included in the predictive cost function J because generating PV power does not incur a cost. However, the power P_{PV} generated by PV panels 308 can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered CEF components 402, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 414 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). The amount of PV power P_{PV} generated during any time step k can be predicted by economic controller 510. Several techniques for predicting the amount of PV power generated by PV panels are described in U.S. Patent Application No. 15/247,869, U.S. Patent Application No. 15/247,844, and U.S. Patent Application No. 15/247,788. Each of these patent applications has a filing date of August 25, 2016, and the entire disclosure of each of these patent applications is incorporated by reference herein.

[0096] Economic controller 510 can optimize the predictive cost function J over the duration of the optimization period to determine optimal values of the decision variables at each time step during the optimization period. In some embodiments, the optimization period has a duration of approximately one day and each time step is approximately fifteen minutes. However, the durations of the optimization period and the time steps can vary in other embodiments and can be adjusted by a user. Advantageously, economic controller 510 can use battery unit 302 to perform load shifting by drawing electricity from energy grid 414 when energy prices are low and/or when the power consumed by powered CEF components 402 is low. The electricity can be stored in battery unit 302 and discharged later when energy prices are high and/or the power consumption of powered CEF components 402 is high. This enables economic controller 510 to reduce the cost of electricity consumed by CEF 300 and can smooth momentary spikes in the electric demand of CEF 300, thereby reducing the demand charge incurred.

[0097] Economic controller 510 can be configured to impose constraints on the optimization of the predictive cost function J . In some embodiments, the constraints include constraints on the temperature T_{zone} of a building zone served by CEF 300. Economic controller 510 can be configured to maintain the actual or predicted temperature T_{zone} between an minimum temperature bound T_{min} and a maximum temperature bound T_{max} (i.e., $T_{min} \leq T_{zone} \leq T_{max}$) at all times. The parameters T_{min} and T_{max} may be time-varying to define different temperature ranges at different times (e.g., an occupied temperature range, an unoccupied temperature range, a daytime temperature range, a nighttime temperature range, etc.).

[0098] In order to ensure that the zone temperature constraint is satisfied, economic controller 510 can model the temperature T_{zone} of the building zone as a function of the decision variables optimized by economic controller 510. In some embodiments, economic controller 510 models the temperature of the building zone using a heat transfer model. For example, the dynamics of heating or cooling the building zone can be described by the energy balance:

$$C \frac{dT_{zone}}{dt} = -H(T_{zone} - T_a) + \dot{Q}_{HVAC} + \dot{Q}_{other}$$

where C is the thermal capacitance of the building zone, H is the ambient heat transfer coefficient for the building zone, T_{zone} is the temperature of the building zone, T_a is the

ambient temperature outside the building zone (e.g., the outside air temperature), $\dot{Q}_{HVAC}$ is the amount of heating applied to the building zone by CEF 300, and $\dot{Q}_{other}$ is the external load, radiation, or other disturbance experienced by the building zone. In the previous equation, $\dot{Q}_{HVAC}$ represents heat transfer into the building zone by CEF 300 (i.e., the heating load) and therefore has a positive sign. However, if cooling is applied to the building zone rather than heating, the sign on $\dot{Q}_{HVAC}$ can be switched to a negative sign such that $\dot{Q}_{HVAC}$ represents the amount of cooling applied to the building zone by CEF 300 (i.e., the cooling load). Several techniques for developing zone temperature models and relating the zone temperature T_{zone} to the decision variables in the predictive cost function J are described in greater detail in U.S. Patent No. 9,436,179 granted September 6, 2016, U.S. Patent Application No. 14/694,633 filed April 23, 2015, and U.S. Patent Application No. 15/199,910 filed June 30, 2016. The entire disclosure of each of these patents and patent applications is incorporated by reference herein.

[0099] The previous energy balance combines all mass and air properties of the building zone into a single zone temperature. Other heat transfer models which can be used by economic controller 510 include the following air and mass zone models:

$$C_z \frac{dT_{zone}}{dt} = H_{az}(T_a - T_{zone}) + H_{mz}(T_m - T_{zone}) + \dot{Q}_{HVAC} + \dot{Q}_{other}$$

$$C_m \frac{dT_m}{dt} = H_{mz}(T_{zone} - T_m)$$

where C_z and T_{zone} are the thermal capacitance and temperature of the air in the building zone, T_a is the ambient air temperature, H_{az} is the heat transfer coefficient between the air of the building zone and ambient air outside the building zone (e.g., through external walls of the building zone), C_m and T_m are the thermal capacitance and temperature of the non-air mass within the building zone, and H_{mz} is the heat transfer coefficient between the air of the building zone and the non-air mass.

[0100] The previous equation combines all mass properties of the building zone into a single zone mass. Other heat transfer models which can be used by economic controller 510 include the following air, shallow mass, and deep mass zone models:

$$C_z \frac{dT_{zone}}{dt} = H_{az}(T_a - T_{zone}) + H_{sz}(T_s - T_{zone}) + \dot{Q}_{HVAC} + \dot{Q}_{other}$$

$$C_s \frac{dT_s}{dt} = H_{sz}(T_{zone} - T_s) + H_{ds}(T_d - T_s)$$

$$C_d \frac{dT_d}{dt} = H_{ds}(T_s - T_d)$$

where C_z and T_{zone} are the thermal capacitance and temperature of the air in the building zone, T_a is the ambient air temperature, H_{az} is the heat transfer coefficient between the air of the building zone and ambient air outside the building zone (e.g., through external walls of the building zone), C_s and T_s are the thermal capacitance and temperature of the shallow mass within the building zone, H_{sz} is the heat transfer coefficient between the air of the building zone and the shallow mass, C_d and T_d are the thermal capacitance and temperature of the deep mass within the building zone, and H_{ds} is the heat transfer coefficient between the shallow mass and the deep mass.

[0101] In some embodiments, economic controller 510 uses the weather forecasts from weather service 416 to determine appropriate values for the ambient air temperature T_a and/or the external disturbance $\dot{Q}_{other}$ at each time step of the optimization period. Values of C and H can be specified as parameters of the building zone, received from tracking controller 512, received from a user, retrieved from memory 508, or otherwise provided as an input to economic controller 510. Accordingly, the temperature of the building zone T_{zone} can be defined as a function of the amount of heating or cooling $\dot{Q}_{HVAC}$ applied to the building zone by CEF 300 using any of these heat transfer models. The manipulated variable $\dot{Q}_{HVAC}$ can be adjusted by economic controller 510 by adjusting the variables $P_{chiller}$, P_{HRC} , F_{gas} and/or P_{total} in the predictive cost function J .

[0102] In some embodiments, economic controller 510 uses a model that defines the amount of heating or cooling $\dot{Q}_{HVAC}$ applied to the building zone by CEF 300 as a function of the power setpoints $P_{sp,grid}$ and $P_{sp,bat}$ provided by economic controller 510. For example, economic controller 510 can add the power setpoints $P_{sp,grid}$ and $P_{sp,bat}$ to determine the total amount of power P_{total} that will be consumed by powered CEF components 402. Economic controller 510 can use P_{total} to determine the total amount of heating or cooling $\dot{Q}_{HVAC}$ applied to the building zone by CEF 300.

[0103] In some embodiments, economic controller 510 uses one or more models that define the amount of heating or cooling applied to the building zone by CEF 300 (i.e., $\dot{Q}_{HVAC}$) as a function of the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$ as shown in the following equation:

$$\dot{Q}_{HVAC} = f(T_{zone}, T_{sp,zone})$$

The models used by economic controller 510 can be imposed as optimization constraints to ensure that the amount of heating or cooling $\dot{Q}_{HVAC}$ provided by CEF 300 is not reduced to a value that would cause the zone temperature T_{zone} to deviate from an acceptable or comfortable temperature range.

[0104] In some embodiments, economic controller 510 relates the amount of heating or cooling $\dot{Q}_{HVAC}$ provided by CEF 300 to the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$ using multiple models. For example, economic controller 510 can use a model of equipment controller 514 to determine the control action performed by equipment controller 514 as a function of the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$. An example of such a zone regulatory controller model is shown in the following equation:

$$v_{air} = f_1(T_{zone}, T_{sp,zone})$$

where v_{air} is the rate of airflow to the building zone (i.e., the control action). The function f_1 can be identified from data. For example, economic controller 510 can collect measurements of v_{air} and T_{zone} and identify the corresponding value of $T_{sp,zone}$. Economic controller 510 can perform a system identification process using the collected values of v_{air} , T_{zone} , and $T_{sp,zone}$ as training data to determine the function f_1 that defines the relationship between such variables.

[0105] Economic controller 510 can use an energy balance model relating the control action v_{air} to the amount of heating or cooling $\dot{Q}_{HVAC}$ provided by CEF 300 as shown in the following equation:

$$\dot{Q}_{HVAC} = f_2(v_{air})$$

where the function f_2 can be identified from training data. Economic controller 510 can perform a system identification process using collected values of v_{air} and $\dot{Q}_{HVAC}$ to determine the function f_2 that defines the relationship between such variables.

[0106] In some embodiments, a linear relationship exists between $\dot{Q}_{HVAC}$ and v_{air} . Assuming an ideal proportional-integral (PI) controller and a linear relationship between $\dot{Q}_{HVAC}$ and v_{air} , a simplified linear controller model can be used to define the amount of heating or cooling $\dot{Q}_{HVAC}$ provided by CEF 300 as a function of the zone temperature T_{zone}

and the zone temperature setpoint $T_{sp,zone}$. An example of such a model is shown in the following equations:

$$\dot{Q}_{HVAC} = \dot{Q}_{ss} + K_c \left[\varepsilon + \frac{1}{\tau_I} \int_0^t \varepsilon(t') dt' \right]$$

$$\varepsilon = T_{sp,zone} - T_{zone}$$

where $\dot{Q}_{ss}$ is the steady-state rate of heating or cooling rate, K_c is the scaled zone PI controller proportional gain, τ_I is the zone PI controller integral time, and ε is the setpoint error (i.e., the difference between the zone temperature setpoint $T_{sp,zone}$ and the zone temperature T_{zone}). Saturation can be represented by constraints on $\dot{Q}_{HVAC}$. If a linear model is not sufficiently accurate to model equipment controller 514 and heat transfer in CEF 300, a nonlinear heating/cooling duty model can be used instead.

[0107] In addition to constraints on the zone temperature T_{zone} , economic controller 510 can impose constraints on the state-of-charge (SOC) and charge/discharge rates of battery unit 302. In some embodiments, economic controller 510 generates and imposes the following power constraints on the predictive cost function J :

$$P_{bat} \leq P_{rated}$$

$$-P_{bat} \leq P_{rated}$$

where P_{bat} is the amount of power discharged from battery unit 302 and P_{rated} is the rated battery power of battery unit 302 (e.g., the maximum rate at which battery unit 302 can be charged or discharged). These power constraints ensure that battery unit 302 is not charged or discharged at a rate that exceeds the maximum possible battery charge/discharge rate P_{rated} .

[0108] In some embodiments, economic controller 510 generates and imposes one or more capacity constraints on the predictive cost function J . The capacity constraints may be used to relate the battery power P_{bat} charged or discharged during each time step to the capacity and SOC of battery unit 302. The capacity constraints may ensure that the capacity of battery unit 302 is maintained within acceptable lower and upper bounds at each time step of the optimization period. In some embodiments, economic controller 510 generates the following capacity constraints:

$$C_a(k) - P_{bat}(k)\Delta t \leq C_{rated}$$

$$C_a(k) - P_{bat}(k)\Delta t \geq 0$$

where $C_a(k)$ is the available battery capacity (e.g., kWh) at the beginning of time step k , $P_{bat}(k)$ is the rate at which battery unit 302 is discharged during time step k (e.g., kW), Δt is the duration of each time step, and C_{rated} is the maximum rated capacity of battery unit 302 (e.g., kWh). The term $P_{bat}(k)\Delta t$ represents the change in battery capacity during time step k . These capacity constraints ensure that the capacity of battery unit 302 is maintained between zero and the maximum rated capacity C_{rated} .

[0109] In some embodiments, economic controller 510 generates and imposes one or more capacity constraints on the operation of powered CEF components 402. For example, powered CEF components 402 may have a maximum operating point (e.g., a maximum pump speed, a maximum cooling capacity, etc.) which corresponds to a maximum power consumption $P_{total,max}$. Economic controller 510 can be configured to generate a constraint which limits the power P_{total} provided to powered CEF components 402 between zero and the maximum power consumption $P_{total,max}$ as shown in the following equation:

$$0 \leq P_{total} \leq P_{total,max}$$

$$P_{total} = P_{sp,grid} + P_{sp,bat}$$

where the total power P_{total} provided to powered CEF components 402 is the sum of the grid power setpoint $P_{sp,grid}$ and the battery power setpoint $P_{sp,bat}$.

[0110] In some embodiments, economic controller 510 generates and imposes one or more capacity constraints on the operation of the one or more subplants of CEF 300. For example, heating may be provided by heater subplant 202 and cooling may be provided by chiller subplant 206. The operation of heater subplant 202 and chiller subplant 206 may be defined by subplant curves for each of heater subplant 202 and chiller subplant 206. Each subplant curve may define the resource production of the subplant (e.g., tons refrigeration, kW heating, etc.) as a function of one or more resources consumed by the subplant (e.g., electricity, natural gas, water, etc.). Several examples of subplant curves which can be used by economic controller 510 are described in greater detail in U.S. Patent Application No. 14/634,609 filed February 27, 2015.

[0111] Economic controller 510 can be configured to use the subplant curves to identify a maximum amount of heating that can be provided by heater subplant 202 and a maximum amount of cooling that can be provided by chiller subplant 206. Economic controller 510 can generate and impose a constraint that limits the amount of heating provided by heater

subplant 202 between zero and the maximum amount of heating. Similarly, economic controller 510 can generate and impose a constraint that limits the amount of cooling provided by chiller subplant 206 between zero and the maximum amount of cooling.

[0112] Economic controller 510 can optimize the predictive cost function J subject to the constraints to determine optimal values for the decision variables P_{total} , $P_{chiller}$, P_{HRC} , F_{gas} , P_{grid} , and P_{bat} , where $P_{total} = P_{bat} + P_{grid} + P_{PV}$. In some embodiments, economic controller 510 uses the optimal values for P_{total} , P_{bat} , and/or P_{grid} to generate power setpoints for tracking controller 512. The power setpoints can include battery power setpoints $P_{sp,bat}$, grid power setpoints $P_{sp,grid}$, and/or CEF power setpoints $P_{sp,total}$ for each of the time steps k in the optimization period. Economic controller 510 can provide the power setpoints to tracking controller 512.

Tracking Controller

[0113] Tracking controller 512 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ generated by economic controller 510 to determine optimal temperature setpoints (e.g., a zone temperature setpoint $T_{sp,zone}$, a chilled water temperature setpoint $T_{sp,chw}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). In some embodiments, tracking controller 512 generates a zone temperature setpoint $T_{sp,zone}$ and/or a chilled water temperature setpoint $T_{sp,chw}$ that are predicted to achieve the power setpoint $P_{sp,total}$ for CEF 300. In other words, tracking controller 512 may generate a zone temperature setpoint $T_{sp,zone}$ and/or a chilled water temperature setpoint $T_{sp,chw}$ that cause CEF 300 to consume the optimal amount of power P_{total} determined by economic controller 510.

[0114] In some embodiments, tracking controller 512 relates the power consumption of CEF 300 to the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$ using a power consumption model. For example, tracking controller 512 can use a model of equipment controller 514 to determine the control action performed by equipment controller 514 as a function of the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$. An example of such a zone regulatory controller model is shown in the following equation:

$$v_{air} = f_3(T_{zone}, T_{sp,zone})$$

where v_{air} is the rate of airflow to the building zone (i.e., the control action).

[0115] Tracking controller 512 can define the power consumption P_{total} of CEF 300 as a function of the zone temperature T_{zone} and the zone temperature setpoint $T_{sp,zone}$. An example of such a model is shown in the following equation:

$$P_{total} = f_4(T_{zone}, T_{sp,zone})$$

The function f_4 can be identified from data. For example, tracking controller 512 can collect measurements of P_{total} and T_{zone} and identify the corresponding value of $T_{sp,zone}$. Tracking controller 512 can perform a system identification process using the collected values of P_{total} , T_{zone} , and $T_{sp,zone}$ as training data to determine the function f_4 that defines the relationship between such variables.

[0116] Tracking controller 512 may use a similar model to determine the relationship between the total power consumption P_{total} of CEF 300 and the chilled water temperature setpoint $T_{sp,chw}$. For example, tracking controller 512 can define the power consumption P_{total} of CEF 300 as a function of the zone temperature T_{zone} and the chilled water temperature setpoint $T_{sp,chw}$. An example of such a model is shown in the following equation:

$$P_{total} = f_5(T_{zone}, T_{sp,chw})$$

The function f_5 can be identified from data. For example, tracking controller 512 can collect measurements of P_{total} and T_{zone} and identify the corresponding value of $T_{sp,chw}$. Tracking controller 512 can perform a system identification process using the collected values of P_{total} , T_{zone} , and $T_{sp,chw}$ as training data to determine the function f_5 that defines the relationship between such variables.

[0117] Tracking controller 512 can use the relationships between P_{total} , $T_{sp,zone}$, and $T_{sp,chw}$ to determine values for $T_{sp,zone}$ and $T_{sp,chw}$. For example, tracking controller 512 can receive the value of P_{total} as an input from economic controller 510 (i.e., $P_{sp,total}$) and can use determine corresponding values of $T_{sp,zone}$ and $T_{sp,chw}$. Tracking controller 512 can provide the values of $T_{sp,zone}$ and $T_{sp,chw}$ as outputs to equipment controller 514.

[0118] In some embodiments, tracking controller 512 uses the battery power setpoint $P_{sp,bat}$ to determine the optimal rate $Bat_{C/D}$ at which to charge or discharge battery unit 302. For example, the battery power setpoint $P_{sp,bat}$ may define a power value (kW) which can be translated by tracking controller 512 into a control signal for power inverter 410 and/or

equipment controller 514. In other embodiments, the battery power setpoint $P_{sp,bat}$ is provided directly to power inverter 410 and used by power inverter 410 to control the battery power P_{bat} .

Equipment Controller

[0119] Equipment controller 514 can use the optimal temperature setpoints $T_{sp,zone}$ or $T_{sp,chw}$ generated by tracking controller 512 to generate control signals for powered CEF components 402. The control signals generated by equipment controller 514 may drive the actual (e.g., measured) temperatures T_{zone} and/or T_{chw} to the setpoints. Equipment controller 514 can use any of a variety of control techniques to generate control signals for powered CEF components 402. For example, equipment controller 514 can use state-based algorithms, extremum seeking control (ESC) algorithms, proportional-integral (PI) control algorithms, proportional-integral-derivative (PID) control algorithms, model predictive control (MPC) algorithms, or other feedback control algorithms, to generate control signals for powered CEF components 402.

[0120] The control signals may include on/off commands, speed setpoints for fans of cooling towers 404, power setpoints for compressors of chillers 406, chilled water temperature setpoints for chillers 406, pressure setpoints or flow rate setpoints for pumps 408, or other types of setpoints for individual devices of powered CEF components 402. In other embodiments, the control signals may include the temperature setpoints (e.g., a zone temperature setpoint $T_{sp,zone}$, a chilled water temperature setpoint $T_{sp,chw}$, etc.) generated by predictive CEF controller 304. The temperature setpoints can be provided to powered CEF components 402 or local controllers for powered CEF components 402 which operate to achieve the temperature setpoints. For example, a local controller for chillers 406 may receive a measurement of the chilled water temperature T_{chw} from chilled water temperature sensor and/or a measurement the zone temperature T_{zone} from a zone temperature sensor.

[0121] In some embodiments, equipment controller 514 is configured to provide control signals to power inverter 410. The control signals provided to power inverter 410 can include a battery power setpoint $P_{sp,bat}$ and/or the optimal charge/discharge rate $Bat_{C/D}$. Equipment controller 514 can be configured to operate power inverter 410 to achieve the battery power setpoint $P_{sp,bat}$. For example, equipment controller 514 can cause power inverter 410 to

charge battery unit 302 or discharge battery unit 302 in accordance with the battery power setpoint $P_{sp,bat}$.

[0122] Referring now to FIG. 6, a user interface 600 which can be generated by predictive CEF controller 304 is shown, according to some embodiments. As discussed above, economic controller 510 can be configured to determine the portion of each power consumption value (e.g., $P_{chiller}$, P_{HRC} , etc.) that consists of grid power and/or battery power at each time step of the optimization period. User interface 600 can be used to convey to a user the relative portions of each power consumption value that consist of grid power and/or battery power.

[0123] Interface 600 illustrates a dispatch chart. The top half of the dispatch chart corresponds to cooling, whereas the bottom half of the dispatch chart corresponds to heating. The midline between the top and bottom halves corresponds to zero load/power for both halves. Positive cooling values are shown as displacement above the midline, whereas positive heating values are shown as displacement below the midline. Lines 602 and 612 represent the requested cooling load and the requested heating load, respectively, at each time step of the optimization period. Lines 604 and 614 represent the charge level of batteries used to power the cooling equipment (e.g., a chiller subplant) and the heating equipment (e.g., a heater subplant) over the duration of the optimization period.

[0124] As discussed above, economic controller 510 can be configured to determine optimal power setpoints for each time step of the optimization period. The results of the optimization performed by economic controller 510 can be represented in the dispatch chart. For example, the dispatch chart is shown to include a vertical column for each time step of the optimization period. Each column may include one or more bars representing the power setpoints determined by economic controller 510 for the corresponding time step. The color of each bar indicates the type of power setpoint. For example, gray bars 608 and 618 (shown as white bars in FIG. 6) may indicate the grid power setpoint (e.g., $P_{sp,grid}$) whereas green bars 606 and 616 (shown as shaded bars in FIG. 6) may indicate the battery power setpoint (e.g., $P_{sp,bat}$). The height of each bar indicates the magnitude of the corresponding power setpoint at that time step.

[0125] Green bars 606 positioned above requested cooling line 602 indicate that the cooling equipment battery is charging (i.e., excess energy used to charge the battery), whereas green bars 606 positioned below requested cooling line 602 indicate that the cooling equipment

battery is discharging (i.e., battery power used to satisfy part of the requested cooling load). The charge level of the cooling equipment battery increases when the cooling equipment battery is charging and decreases when the cooling equipment battery is discharging.

[0126] Similarly, green bars 616 positioned below requested heating line 612 indicate that the heating equipment battery is charging (i.e., excess energy used to charge the battery), whereas green bars 616 positioned above requested heating line 612 indicate that the heating equipment battery is discharging (i.e., battery power used to satisfy part of the requested heating load). The charge level of the heating equipment battery increases when the heating equipment battery is charging and decreases when the heating equipment battery is discharging.

Air Cooled Chiller With Battery Unit and Predictive Control

[0127] Referring now to FIGS. 7-8, an air-cooled chiller 700 with a battery unit 702 and predictive chiller controller 704 is shown, according to some embodiments. Chiller 700 can be configured to provide a chilled fluid (e.g., chilled water 718) to a cooling load 734 via chilled water pipe 714. Cooling load 734 can include, for example, a building zone, a supply airstream flowing through an air duct, an airflow in an air handling unit or rooftop unit, fluid flowing through a heat exchanger, a refrigerator or freezer, a condenser or evaporator, a cooling coil, or any other type of system, device, or space which requires cooling. In some embodiments, a pump 732 circulates a chilled fluid to cooling load 734 via a chilled fluid circuit 738. The chilled fluid can absorb heat from cooling load 734, thereby providing cooling to cooling load 734 and warming the chilled fluid. The warmed fluid (shown in FIG. 7 as return water 716) may return to chiller 700 via return water pipe 712.

[0128] Chiller 700 is shown to include a condenser 722, a compressor 720, an evaporator 724, an expansion device 726, and a fan 730. Compressor 720 can be configured to circulate a refrigerant between condenser 722 and evaporator 724 via refrigeration circuit 736. Compressor 720 operates to compress the refrigerant to a high pressure, high temperature state. The compressed refrigerant flows through condenser 722, which transfers heat from the refrigerant in refrigeration circuit 736 to an airflow 728. A fan 730 can be used to force airflow 728 through or over condenser 722 to provide cooling for the refrigerant in condenser 722. The cooled refrigerant then flows through expansion device 726, which expands the refrigerant to a low temperature, low pressure state. The expanded refrigerant flows through

evaporator 724, which transfers heat from the chilled fluid in chilled fluid circuit 738 to the refrigerant in refrigeration circuit 736.

[0129] In some embodiments, chiller 700 includes one or more photovoltaic (PV) panels 708. PV panels 708 may include a collection of photovoltaic cells. The photovoltaic cells are configured to convert solar energy (i.e., sunlight) into electricity using a photovoltaic material such as monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, copper indium gallium selenide/sulfide, or other materials that exhibit the photovoltaic effect. In some embodiments, the photovoltaic cells are contained within packaged assemblies that form PV panels 708. Each PV panel 708 may include a plurality of linked photovoltaic cells. PV panels 708 may combine to form a photovoltaic array.

[0130] In some embodiments, PV panels 708 are configured to maximize solar energy collection. For example, chiller 700 may include a solar tracker (e.g., a GPS tracker, a sunlight sensor, etc.) that adjusts the angle of PV panels 708 so that PV panels 708 are aimed directly at the sun throughout the day. The solar tracker may allow PV panels 708 to receive direct sunlight for a greater portion of the day and may increase the total amount of power produced by PV panels 708. In some embodiments, chiller 700 includes a collection of mirrors, lenses, or solar concentrators configured to direct and/or concentrate sunlight on PV panels 708. The energy generated by PV panels 708 may be stored in battery unit 702 and/or used to power various components of chiller 700.

[0131] In some embodiments, battery unit 702 includes one or more battery cells 706. Battery cells 706 are configured to store and discharge electric energy (i.e., electricity). In some embodiments, battery unit 702 is charged using electricity from an external energy grid (e.g., provided by an electric utility). The electricity stored in battery unit 702 can be discharged to power one or more powered components of chiller 700 (e.g., fan 730, compressor 720, pump 732, etc.). Advantageously, battery unit 702 allows chiller 700 to draw electricity from the energy grid and charge battery unit 702 when energy prices are low and discharge the stored electricity when energy prices are high to time-shift the electric load of chiller 700. In some embodiments, battery unit 702 has sufficient energy capacity to power chiller 700 for approximately 4-6 hours when operating at maximum capacity such that battery unit 702 can be utilized during high energy cost periods and charged during low energy cost periods.

[0132] In some embodiments, predictive chiller controller 704 performs an optimization process to determine whether to charge or discharge battery unit 702 during each of a plurality of time steps that occur during an optimization period. Predictive chiller controller 704 may use weather and pricing data 710 to predict the amount of heating/cooling required and the cost of electricity during each of the plurality of time steps. Predictive chiller controller 704 can optimize an objective function that accounts for the cost of electricity purchased from the energy grid over the duration of the optimization period. Predictive chiller controller 704 can determine an amount of electricity to purchase from the energy grid and an amount of electricity to store or discharge from battery unit 702 during each time step. The objective function and the optimization performed by predictive chiller controller 704 are described in greater detail with reference to FIGS. 9-10.

Predictive Chiller Control System

[0133] Referring now to FIG. 9, a block diagram of a predictive chiller control system 900 is shown, according to some embodiments. Several of the components shown in control system 900 may be part of chiller 700. For example, chiller 700 may include powered chiller components 902, battery unit 702, predictive chiller controller 704, power inverter 910, and a power junction 912. Powered chiller components 902 may include any component of chiller 700 that consumes power (e.g., electricity) during operation. For example, powered chiller components 902 are shown to include cooling fan 730, compressor 720, and pump 732.

[0134] Power inverter 910 may be configured to convert electric power between direct current (DC) and alternating current (AC). For example, battery unit 702 may be configured to store and output DC power, whereas energy grid 914 and powered chiller components 902 may be configured to consume and provide AC power. Power inverter 910 may be used to convert DC power from battery unit 702 into a sinusoidal AC output synchronized to the grid frequency of energy grid 914 and/or powered chiller components 902. Power inverter 910 may also be used to convert AC power from energy grid 914 into DC power that can be stored in battery unit 702. The power output of battery unit 702 is shown as P_{bat} . P_{bat} may be positive if battery unit 702 is providing power to power inverter 910 (i.e., battery unit 702 is discharging) or negative if battery unit 702 is receiving power from power inverter 910 (i.e., battery unit 702 is charging).

[0135] In some instances, power inverter 910 receives a DC power output from battery unit 702 and converts the DC power output to an AC power output that can be provided to

powered chiller components 902. Power inverter 910 may synchronize the frequency of the AC power output with that of energy grid 914 (e.g., 50 Hz or 60 Hz) using a local oscillator and may limit the voltage of the AC power output to no higher than the grid voltage. In some embodiments, power inverter 910 is a resonant inverter that includes or uses LC circuits to remove the harmonics from a simple square wave in order to achieve a sine wave matching the frequency of energy grid 914. In various embodiments, power inverter 910 may operate using high-frequency transformers, low-frequency transformers, or without transformers. Low-frequency transformers may convert the DC output from battery unit 702 directly to the AC output provided to powered chiller components 902. High-frequency transformers may employ a multi-step process that involves converting the DC output to high-frequency AC, then back to DC, and then finally to the AC output provided to powered chiller components 902.

[0136] The power output of PV panels 708 is shown as P_{PV} . The power output P_{PV} of PV panels 708 can be stored in battery unit 702 and/or used to power powered chiller components 902. In some embodiments, PV panels 708 measure the amount of power P_{PV} generated by PV panels 708 and provides an indication of the PV power to predictive chiller controller 704. For example, PV panels 708 are shown providing an indication of the PV power percentage (i.e., PV %) to predictive chiller controller 704. The PV power percentage may represent a percentage of the maximum PV power at which PV panels 708 are currently operating.

[0137] Power junction 912 is the point at which powered chiller components 902, energy grid 914, PV panels 708, and power inverter 910 are electrically connected. The power supplied to power junction 912 from power inverter 910 is shown as P_{bat} . P_{bat} may be positive if power inverter 910 is providing power to power junction 912 (i.e., battery unit 702 is discharging) or negative if power inverter 910 is receiving power from power junction 912 (i.e., battery unit 702 is charging). The power supplied to power junction 912 from energy grid 914 is shown as P_{grid} and the power supplied to power junction 912 from PV panels 708 is shown as P_{PV} . P_{bat} , P_{PV} , and P_{grid} combine at power junction 912 to form P_{total} (i.e., $P_{total} = P_{grid} + P_{bat} + P_{PV}$). P_{total} may be defined as the power provided to powered chiller components 902 from power junction 912. In some instances, P_{total} is greater than P_{grid} . For example, when battery unit 702 is discharging, P_{bat} may be positive which adds to the grid power P_{grid} and the PV power P_{PV} when P_{bat} and P_{PV} combine with P_{grid} to form

P_{total} . In other instances, P_{total} may be less than P_{grid} . For example, when battery unit 702 is charging, P_{bat} may be negative which subtracts from the grid power P_{grid} and the PV power P_{PV} when P_{bat} , P_{PV} , and P_{grid} combine to form P_{total} .

[0138] Predictive chiller controller 704 can be configured to control powered chiller components 902 and power inverter 910. In some embodiments, predictive chiller controller 704 generates and provides a battery power setpoint $P_{sp,bat}$ to power inverter 910. The battery power setpoint $P_{sp,bat}$ may include a positive or negative power value (e.g., kW) which causes power inverter 910 to charge battery unit 702 (when $P_{sp,bat}$ is negative) using power available at power junction 912 or discharge battery unit 702 (when $P_{sp,bat}$ is positive) to provide power to power junction 912 in order to achieve the battery power setpoint $P_{sp,bat}$.

[0139] In some embodiments, predictive chiller controller 704 generates and provides control signals to powered chiller components 902. Predictive chiller controller 704 may use a multi-stage optimization technique to generate the control signals. For example, predictive chiller controller 704 may include an economic controller configured to determine the optimal amount of power to be consumed by powered chiller components 902 at each time step during the optimization period. The optimal amount of power to be consumed may minimize a cost function that accounts for the cost of energy consumed by chiller 700. The cost of energy may be based on time-varying energy prices from electric utility 918. In some embodiments, predictive chiller controller 704 determines an optimal amount of power to purchase from energy grid 914 (i.e., a grid power setpoint $P_{sp,grid}$) and an optimal amount of power to store or discharge from battery unit 702 (i.e., a battery power setpoint $P_{sp,bat}$) at each of the plurality of time steps. Predictive chiller controller 704 may monitor the actual power usage of powered chiller components 902 and may utilize the actual power usage as a feedback signal when generating the optimal power setpoints.

[0140] Predictive chiller controller 704 may include a tracking controller configured to generate temperature setpoints (e.g., an air temperature setpoint $T_{sp,air}$, a chilled water temperature setpoint $T_{sp,water}$, etc.) that achieve the optimal amount of power consumption at each time step. In some embodiments, predictive chiller controller 704 uses equipment models for powered chiller components 902 to determine an amount of heating or cooling that can be generated by chiller components 902 based on the optimal amount of power

consumption. Predictive chiller controller 704 can use a temperature model to predict how the temperature of the chilled water T_{water} will change based on the power setpoints.

[0141] In some embodiments, predictive chiller controller 704 uses the temperature setpoints to generate the control signals for powered chiller components 902. The control signals may include on/off commands, speed setpoints for fan 730, power setpoints for compressor 720, chilled water temperature setpoints chiller 700, pressure setpoints or flow rate setpoints for pump 732, or other types of setpoints for individual devices of powered chiller components 902. In other embodiments, the control signals may include the temperature setpoints (e.g., an air temperature setpoint $T_{sp,air}$, a chilled water temperature setpoint $T_{sp,water}$, etc.) generated by predictive chiller controller 704. The temperature setpoints can be provided to powered chiller components 902 or local controllers for powered chiller components 902 which operate to achieve the temperature setpoints. For example, a local controller for fan 730 may receive a measurement of the chilled water temperature T_{water} from a chilled water temperature sensor and/or a measurement the air temperature T_{air} (i.e., the temperature of airflow 728) from an air temperature sensor. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to increase or decrease the airflow provided by fan 730 to drive the measured temperature(s) to the temperature setpoint(s). Similar feedback control processes can be used to compressor 720 and/or pump 732. The multi-stage optimization performed by predictive chiller controller 704 is described in greater detail with reference to FIG. 10.

Predictive Chiller Controller

[0142] Referring now to FIG. 10, a block diagram illustrating predictive chiller controller 704 in greater detail is shown, according to an exemplary embodiment. Predictive chiller controller 704 is shown to include a communications interface 1002 and a processing circuit 1004. Communications interface 1002 may facilitate communications between controller 704 and external systems or devices. For example, communications interface 1002 may receive measurements of the air temperature T_{air} and the chilled water temperature T_{water} from temperature sensors 1016 and measurements of the power usage of powered chiller components 902. In some embodiments, communications interface 1002 receives measurements of the state-of-charge (SOC) of battery unit 702, which can be provided as a percentage of the maximum battery capacity (i.e., battery %). Communications interface 1002 can receive weather forecasts from a weather service 916 and predicted energy costs

and demand costs from an electric utility 918. In some embodiments, predictive chiller controller 704 uses communications interface 1002 to provide control signals powered chiller components 902 and power inverter 910.

[0143] Communications interface 1002 may include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications external systems or devices. In various embodiments, the communications may be direct (e.g., local wired or wireless communications) or via a communications network (e.g., a WAN, the Internet, a cellular network, etc.). For example, communications interface 1002 can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, communications interface 1002 can include a Wi-Fi transceiver for communicating via a wireless communications network or cellular or mobile phone communications transceivers.

[0144] Processing circuit 1004 is shown to include a processor 1006 and memory 1008. Processor 1006 may be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Processor 1006 is configured to execute computer code or instructions stored in memory 1008 or received from other computer readable media (e.g., CDROM, network storage, a remote server, etc.).

[0145] Memory 1008 may include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory 1008 may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory 1008 may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. Memory 1008 may be communicably connected to processor 1006 via processing circuit 1004 and may include computer code for executing (e.g., by processor 1006) one or more processes described herein. When processor 1006 executes instructions stored in memory 1008 for completing the various activities described herein, processor 1006 generally configures controller 704 (and more particularly processing circuit 1004) to complete such activities.

[0146] Still referring to FIG. 10, predictive chiller controller 704 is shown to include an economic controller 1010, a tracking controller 1012, and an equipment controller 1014. Controllers 1010-1014 can be configured to perform a multi-state optimization process to generate control signals for power inverter 910 and powered chiller components 902. In brief overview, economic controller 1010 can optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 914 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 702 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered chiller components 902 (i.e., a chiller power setpoint $P_{sp,total}$) at each time step of an optimization period. Tracking controller 1012 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ to determine optimal temperature setpoints (e.g., an air setpoint $T_{sp,air}$, a chilled water temperature setpoint $T_{sp,water}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). Equipment controller 1014 can use the optimal temperature setpoints $T_{sp,air}$ or $T_{sp,water}$ to generate control signals for powered chiller components 902 that drive the actual (e.g., measured) temperatures T_{air} and/or T_{water} to the setpoints (e.g., using a feedback control technique). Each of controllers 1010-1014 is described in detail below.

Economic Controller

[0147] Economic controller 1010 can be configured to optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 914 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 702 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered chiller components 902 (i.e., a chiller power setpoint $P_{sp,total}$) at each time step of an optimization period. An example of a predictive cost function which can be optimized by economic controller 1010 is shown in the following equation:

$$\begin{aligned} \min(J) = & \sum_{k=1}^h C_{ec}(k)P_{fan}(k)\Delta t + \sum_{k=1}^h C_{ec}(k)P_{comp}(k)\Delta t + \sum_{k=1}^h C_{ec}(k)P_{pump}(k)\Delta t \\ & + C_{DC} \max_k(P_{grid}(k)) - \sum_{k=1}^h C_{ec}(k)P_{bat}(k)\Delta t \end{aligned}$$

where $C_{ec}(k)$ is the cost per unit of electricity (e.g., \$/kWh) purchased from electric utility 918 during time step k , $P_{fan}(k)$ is the power consumption (e.g., kW) of fan 730 during time step k , $P_{comp}(k)$ is the power consumption of compressor 720 at time step k , $P_{pump}(k)$ is the power consumption of pump 732 at time step k , C_{DC} is the demand charge rate (e.g., \$/kW), where the $\max(\cdot)$ term selects the maximum electricity purchase of chiller 700 (i.e., the maximum value of $P_{grid}(k)$) during any time step k of the optimization period, $P_{bat}(k)$ is the amount of power discharged from battery unit 702 during time step k , and Δt is the duration of each time step k . Economic controller 1010 can optimize the predictive cost function J over the duration of the optimization period (e.g., from time step $k = 1$ to time step $k = h$) to predict the total cost of operating chiller 700 over the duration of the optimization period.

[0148] The first, second, and third terms of the predictive cost function J represent the cost of electricity consumed by powered chiller components 902 over the duration of the optimization period. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 918. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variables $P_{fan}(k)$, $P_{comp}(k)$, and $P_{pump}(k)$ are decision variables which can be optimized by economic controller 1010. In some embodiments, the total power consumption $P_{total}(k)$ of powered chiller components 902 at time step k is equal to the sum of $P_{fan}(k)$, $P_{comp}(k)$, and $P_{pump}(k)$ (i.e., $P_{total}(k) = P_{fan}(k) + P_{comp}(k) + P_{pump}(k)$). Accordingly, the first three terms of the predictive cost function can be replaced with the summation $\sum_{k=1}^h C_{ec}(k)P_{total}(k)\Delta t$ in some embodiments.

[0149] The fourth term of the predictive cost function J represents the demand charge. Demand charge is an additional charge imposed by some utility providers based on the maximum power consumption during an applicable demand charge period. For example, the demand charge rate C_{DC} may be specified in terms of dollars per unit of power (e.g., \$/kW) and may be multiplied by the peak power usage (e.g., kW) during a demand charge period to calculate the demand charge. In the predictive cost function J , the demand charge rate C_{DC} may be defined by the demand cost information received from electric utility 918. The variable $P_{grid}(k)$ is a decision variable which can be optimized by economic controller 1010 in order to reduce the peak power usage $\max(P_{grid}(k))$ that occurs during the demand charge period. Load shifting may allow economic controller 1010 to smooth momentary spikes in the electric demand of chiller 700 by storing energy in battery unit 702 when the power

consumption of powered chiller components 902 is low. The stored energy can be discharged from battery unit 702 when the power consumption of powered chiller components 902 is high in order to reduce the peak power draw P_{grid} from energy grid 914, thereby decreasing the demand charge incurred.

[0150] The final term of the predictive cost function J represents the cost savings resulting from the use of battery unit 702. Unlike the previous terms in the cost function J , the final term subtracts from the total cost. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 918. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{bat}(k)$ is a decision variable which can be optimized by economic controller 1010. A positive value of $P_{bat}(k)$ indicates that battery unit 702 is discharging, whereas a negative value of $P_{bat}(k)$ indicates that battery unit 702 is charging. The power discharged from battery unit 702 $P_{bat}(k)$ can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered chiller components 902, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 914 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). However, charging battery unit 702 results in a negative value of $P_{bat}(k)$ which adds to the total amount of power $P_{grid}(k)$ purchased from energy grid 914.

[0151] In some embodiments, the power P_{PV} provided by PV panels 708 is not included in the predictive cost function J because generating PV power does not incur a cost. However, the power P_{PV} generated by PV panels 708 can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered chiller components 902, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 914 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). The amount of PV power P_{PV} generated during any time step k can be predicted by economic controller 1010. Several techniques for predicting the amount of PV power generated by PV panels are described in U.S. Patent Application No. 15/247,869, U.S. Patent Application No. 15/247,844, and U.S. Patent Application No. 15/247,788. Each of these patent applications has a filing date of August 25, 2016, and the entire disclosure of each of these patent applications is incorporated by reference herein.

[0152] Economic controller 1010 can optimize the predictive cost function J over the duration of the optimization period to determine optimal values of the decision variables at each time step during the optimization period. In some embodiments, the optimization period

has a duration of approximately one day and each time step is approximately fifteen minutes. However, the durations of the optimization period and the time steps can vary in other embodiments and can be adjusted by a user. Advantageously, economic controller 1010 can use battery unit 702 to perform load shifting by drawing electricity from energy grid 914 when energy prices are low and/or when the power consumed by powered chiller components 902 is low. The electricity can be stored in battery unit 702 and discharged later when energy prices are high and/or the power consumption of powered chiller components 902 is high. This enables economic controller 1010 to reduce the cost of electricity consumed by chiller 700 and can smooth momentary spikes in the electric demand of chiller 700, thereby reducing the demand charge incurred.

[0153] Economic controller 1010 can be configured to impose constraints on the optimization of the predictive cost function J . In some embodiments, the constraints include constraints on the temperature T_{water} of the chilled water produced by chiller 700. Economic controller 1010 can be configured to maintain the actual or predicted temperature T_{water} between a minimum temperature bound T_{min} and a maximum temperature bound T_{max} (i.e., $T_{min} \leq T_{water} \leq T_{max}$) at all times. The parameters T_{min} and T_{max} may be time-varying to define different temperature ranges at different times.

[0154] In addition to constraints on the water temperature T_{water} , economic controller 1010 can impose constraints on the state-of-charge (SOC) and charge/discharge rates of battery unit 702. In some embodiments, economic controller 1010 generates and imposes the following power constraints on the predictive cost function J :

$$\begin{aligned} P_{bat} &\leq P_{rated} \\ -P_{bat} &\leq P_{rated} \end{aligned}$$

where P_{bat} is the amount of power discharged from battery unit 702 and P_{rated} is the rated battery power of battery unit 702 (e.g., the maximum rate at which battery unit 702 can be charged or discharged). These power constraints ensure that battery unit 702 is not charged or discharged at a rate that exceeds the maximum possible battery charge/discharge rate P_{rated} .

[0155] In some embodiments, economic controller 1010 generates and imposes one or more capacity constraints on the predictive cost function J . The capacity constraints may be used to relate the battery power P_{bat} charged or discharged during each time step to the capacity and

SOC of battery unit 702. The capacity constraints may ensure that the capacity of battery unit 702 is maintained within acceptable lower and upper bounds at each time step of the optimization period. In some embodiments, economic controller 1010 generates the following capacity constraints:

$$\begin{aligned} C_a(k) - P_{bat}(k)\Delta t &\leq C_{rated} \\ C_a(k) - P_{bat}(k)\Delta t &\geq 0 \end{aligned}$$

where $C_a(k)$ is the available battery capacity (e.g., kWh) at the beginning of time step k , $P_{bat}(k)$ is the rate at which battery unit 702 is discharged during time step k (e.g., kW), Δt is the duration of each time step, and C_{rated} is the maximum rated capacity of battery unit 702 (e.g., kWh). The term $P_{bat}(k)\Delta t$ represents the change in battery capacity during time step k . These capacity constraints ensure that the capacity of battery unit 702 is maintained between zero and the maximum rated capacity C_{rated} .

[0156] In some embodiments, economic controller 1010 generates and imposes one or more capacity constraints on the operation of powered chiller components 902. For example, powered chiller components 902 may have a maximum operating point (e.g., a maximum pump speed, a maximum cooling capacity, etc.) which corresponds to a maximum power consumption $P_{total,max}$. Economic controller 1010 can be configured to generate a constraint which limits the power P_{total} provided to powered chiller components 902 between zero and the maximum power consumption $P_{total,max}$ as shown in the following equation:

$$\begin{aligned} 0 &\leq P_{total} \leq P_{total,max} \\ P_{total} &= P_{sp,grid} + P_{sp,bat} \end{aligned}$$

where the total power P_{total} provided to powered chiller components 902 is the sum of the grid power setpoint $P_{sp,grid}$ and the battery power setpoint $P_{sp,bat}$.

[0157] Economic controller 1010 can optimize the predictive cost function J subject to the constraints to determine optimal values for the decision variables P_{total} , P_{fan} , P_{comp} , P_{pump} , P_{grid} , and P_{bat} , where $P_{total} = P_{bat} + P_{grid} + P_{PV}$. In some embodiments, economic controller 1010 uses the optimal values for P_{total} , P_{bat} , and/or P_{grid} to generate power setpoints for tracking controller 1012. The power setpoints can include battery power setpoints $P_{sp,bat}$, grid power setpoints $P_{sp,grid}$, and/or chiller power setpoints $P_{sp,total}$ for each of the time steps k in the optimization period. Economic controller 1010 can provide the power setpoints to tracking controller 1012.

Tracking Controller

[0158] Tracking controller 1012 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ generated by economic controller 1010 to determine optimal temperature setpoints (e.g., an air temperature setpoint $T_{sp,air}$, a chilled water temperature setpoint $T_{sp,water}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). In some embodiments, tracking controller 1012 generates an air temperature setpoint $T_{sp,air}$ and/or a chilled water temperature setpoint $T_{sp,water}$ that are predicted to achieve the power setpoint $P_{sp,total}$ for chiller 700. In other words, tracking controller 1012 may generate an air temperature setpoint $T_{sp,air}$ and/or a chilled water temperature setpoint $T_{sp,water}$ that cause chiller 700 to consume the optimal amount of power P_{total} determined by economic controller 1010.

[0159] In some embodiments, tracking controller 1012 uses the battery power setpoint $P_{sp,bat}$ to determine the optimal rate $Bat_{C/D}$ at which to charge or discharge battery unit 702. For example, the battery power setpoint $P_{sp,bat}$ may define a power value (kW) which can be translated by tracking controller 1012 into a control signal for power inverter 910 and/or equipment controller 1014. In other embodiments, the battery power setpoint $P_{sp,bat}$ is provided directly to power inverter 910 and used by power inverter 910 to control the battery power P_{bat} .

Equipment Controller

[0160] Equipment controller 1014 can use the optimal temperature setpoints $T_{sp,air}$ or $T_{sp,water}$ generated by tracking controller 1012 to generate control signals for powered chiller components 902. The control signals generated by equipment controller 1014 may drive the actual (e.g., measured) temperatures T_{air} and/or T_{water} to the setpoints. Equipment controller 1014 can use any of a variety of control techniques to generate control signals for powered chiller components 902. For example, equipment controller 1014 can use state-based algorithms, extremum seeking control (ESC) algorithms, proportional-integral (PI) control algorithms, proportional-integral-derivative (PID) control algorithms, model predictive control (MPC) algorithms, or other feedback control algorithms, to generate control signals for powered chiller components 902.

[0161] The control signals may include on/off commands, speed setpoints for fan 730, power setpoints for compressor 720, pressure setpoints or flow rate setpoints for pump 732, or other types of setpoints for individual devices of powered chiller components 902. In other embodiments, the control signals may include the temperature setpoints (e.g., an air temperature setpoint $T_{sp,air}$, a chilled water temperature setpoint $T_{sp,water}$, etc.) generated by predictive chiller controller 704. The temperature setpoints can be provided to powered chiller components 902 or local controllers for powered chiller components 902 which operate to achieve the temperature setpoints. For example, a local controller for fan 730 may receive a measurement of the chilled water temperature T_{water} from chilled water temperature sensor and/or a measurement the air temperature T_{air} from an air temperature sensor and can modulate the speed of fan 730 to drive the measured temperatures to the temperature setpoints.

[0162] In some embodiments, equipment controller 1014 is configured to provide control signals to power inverter 910. The control signals provided to power inverter 910 can include a battery power setpoint $P_{sp,bat}$ and/or the optimal charge/discharge rate $Bat_{C/D}$. Equipment controller 1014 can be configured to operate power inverter 910 to achieve the battery power setpoint $P_{sp,bat}$. For example, equipment controller 1014 can cause power inverter 910 to charge battery unit 702 or discharge battery unit 702 in accordance with the battery power setpoint $P_{sp,bat}$.

Pump Unit With Battery and Predictive Control

[0163] Referring now to FIGS. 11-12, a pump unit 1100 with a battery unit 1102 and predictive pump controller 1104 is shown, according to some embodiments. Pump unit 1100 can be configured to circulate a fluid through a HVAC device 1134 via a fluid circuit 1138. HVAC device 1134 can include, for example, a heating coil or cooling coil, an air handling unit, a rooftop unit, a heat exchanger, a refrigerator or freezer, a condenser or evaporator, a cooling tower, or any other type of system or device that receives a fluid in a HVAC system. In some embodiments, a pump 1132 receives the fluid (e.g., inlet water 1116) via an inlet water pipe 1112 and outputs the fluid (e.g., outlet water 1118) via an outlet water pipe 1114.

[0164] In some embodiments, battery unit 1102 includes one or more battery cells 1106. Battery cells 1106 are configured to store and discharge electric energy (i.e., electricity). In some embodiments, battery unit 1102 is charged using electricity from an external energy grid (e.g., provided by an electric utility). The electricity stored in battery unit 1102 can be

discharged to power one or more powered components of pump unit 1100 (e.g., pump 1132). Advantageously, battery unit 1102 allows pump unit 1100 to draw electricity from the energy grid and charge battery unit 1102 when energy prices are low and discharge the stored electricity when energy prices are high to time-shift the electric load of pump unit 1100. In some embodiments, battery unit 1102 has sufficient energy capacity to power pump unit 1100 for approximately 4-6 hours when operating at maximum capacity such that battery unit 1102 can be utilized during high energy cost periods and charged during low energy cost periods.

[0165] In some embodiments, predictive pump controller 1104 performs an optimization process to determine whether to charge or discharge battery unit 1102 during each of a plurality of time steps that occur during an optimization period. Predictive pump controller 1104 may use weather and pricing data 1110 to predict the amount of heating/cooling required and the cost of electricity during each of the plurality of time steps. Predictive pump controller 1104 can optimize an objective function that accounts for the cost of electricity purchased from the energy grid over the duration of the optimization period. Predictive pump controller 1104 can determine an amount of electricity to purchase from the energy grid and an amount of electricity to store or discharge from battery unit 1102 during each time step. The objective function and the optimization performed by predictive pump controller 1104 are described in greater detail with reference to FIGS. 13-14.

Predictive Pump Control System

[0166] Referring now to FIG. 13, a block diagram of a predictive pump control system 1300 is shown, according to some embodiments. Several of the components shown in control system 1300 may be part of pump unit 1100. For example, pump unit 1100 may include pump 1132, battery unit 1102, predictive pump controller 1104, power inverter 1310, and a power junction 1312.

[0167] Power inverter 1310 may be configured to convert electric power between direct current (DC) and alternating current (AC). For example, battery unit 1102 may be configured to store and output DC power, whereas energy grid 1314 and pump 1132 may be configured to consume and provide AC power. Power inverter 1310 may be used to convert DC power from battery unit 1102 into a sinusoidal AC output synchronized to the grid frequency of energy grid 1314 and/or pump 1132. Power inverter 1310 may also be used to convert AC power from energy grid 1314 into DC power that can be stored in battery unit 1102. The power output of battery unit 1102 is shown as P_{bat} . P_{bat} may be positive if battery unit 1102

is providing power to power inverter 1310 (i.e., battery unit 1102 is discharging) or negative if battery unit 1102 is receiving power from power inverter 1310 (i.e., battery unit 1102 is charging).

[0168] In some instances, power inverter 1310 receives a DC power output from battery unit 1102 and converts the DC power output to an AC power output that can be provided to pump 1132. Power inverter 1310 may synchronize the frequency of the AC power output with that of energy grid 1314 (e.g., 50 Hz or 60 Hz) using a local oscillator and may limit the voltage of the AC power output to no higher than the grid voltage. In some embodiments, power inverter 1310 is a resonant inverter that includes or uses LC circuits to remove the harmonics from a simple square wave in order to achieve a sine wave matching the frequency of energy grid 1314. In various embodiments, power inverter 1310 may operate using high-frequency transformers, low-frequency transformers, or without transformers. Low-frequency transformers may convert the DC output from battery unit 1102 directly to the AC output provided to pump 1132. High-frequency transformers may employ a multi-step process that involves converting the DC output to high-frequency AC, then back to DC, and then finally to the AC output provided to pump 1132.

[0169] Power junction 1312 is the point at which pump 1132, energy grid 1314, and power inverter 1310 are electrically connected. The power supplied to power junction 1312 from power inverter 1310 is shown as P_{bat} . P_{bat} may be positive if power inverter 1310 is providing power to power junction 1312 (i.e., battery unit 1102 is discharging) or negative if power inverter 1310 is receiving power from power junction 1312 (i.e., battery unit 1102 is charging). The power supplied to power junction 1312 from energy grid 1314 is shown as P_{grid} . P_{bat} and P_{grid} combine at power junction 1312 to form P_{total} (i.e., $P_{total} = P_{grid} + P_{bat}$). P_{total} may be defined as the power provided to pump 1132 from power junction 1312. In some instances, P_{total} is greater than P_{grid} . For example, when battery unit 1102 is discharging, P_{bat} may be positive which adds to the grid power P_{grid} when P_{bat} combines with P_{grid} to form P_{total} . In other instances, P_{total} may be less than P_{grid} . For example, when battery unit 1102 is charging, P_{bat} may be negative which subtracts from the grid power P_{grid} when P_{bat} and P_{grid} combine to form P_{total} .

[0170] Predictive pump controller 1104 can be configured to control pump 1132 and power inverter 1310. In some embodiments, predictive pump controller 1104 generates and provides a battery power setpoint $P_{sp,bat}$ to power inverter 1310. The battery power setpoint

$P_{sp,bat}$ may include a positive or negative power value (e.g., kW) which causes power inverter 1310 to charge battery unit 1102 (when $P_{sp,bat}$ is negative) using power available at power junction 1312 or discharge battery unit 1102 (when $P_{sp,bat}$ is positive) to provide power to power junction 1312 in order to achieve the battery power setpoint $P_{sp,bat}$.

[0171] In some embodiments, predictive pump controller 1104 generates and provides control signals to pump 1132. Predictive pump controller 1104 may use a multi-stage optimization technique to generate the control signals. For example, predictive pump controller 1104 may include an economic controller configured to determine the optimal amount of power to be consumed by pump 1132 at each time step during the optimization period. The optimal amount of power to be consumed may minimize a cost function that accounts for the cost of energy consumed by pump unit 1100. The cost of energy may be based on time-varying energy prices from electric utility 1318. In some embodiments, predictive pump controller 1104 determines an optimal amount of power to purchase from energy grid 1314 (i.e., a grid power setpoint $P_{sp,grid}$) and an optimal amount of power to store or discharge from battery unit 1102 (i.e., a battery power setpoint $P_{sp,bat}$) at each of the plurality of time steps. Predictive pump controller 1104 may monitor the actual power usage of pump 1132 and may utilize the actual power usage as a feedback signal when generating the optimal power setpoints.

[0172] Predictive pump controller 1104 may include a tracking controller configured to generate flow setpoints $Flow_{sp}$ and differential pressure setpoints DP_{sp} that achieve the optimal amount of power consumption at each time step. In some embodiments, predictive pump controller 1104 uses an equipment model for pump 1132 to determine an amount of fluid flow and/or differential pressure to be generated by pump 1132 based on the optimal amount of power consumption.

[0173] In some embodiments, predictive pump controller 1104 uses the flow setpoints $Flow_{sp}$ and differential pressure setpoints DP_{sp} to generate the control signals for pump 1132. The control signals may include on/off commands, speed setpoints, or other types of setpoints that affect the operation of pump 1132. In other embodiments, the control signals may include the flow setpoints $Flow_{sp}$ and differential pressure setpoints DP_{sp} generated by predictive pump controller 1104. The setpoints can be provided to pump 1132 or local controllers for pump 1132 which operate to achieve the setpoints. For example, a local controller for pump 1132 may receive a measurement of the differential pressure DP across

pump 1132 from one or more pressure sensors and/or a measurement of the fluid flow caused by pump 1132 from one or more flow sensors. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to increase or decrease the speed of pump 1132 to drive the measured fluid flow and/or differential pressure to the setpoint(s). The multi-stage optimization performed by predictive pump controller 1104 is described in greater detail with reference to FIG. 14.

Predictive Pump Controller

[0174] Referring now to FIG. 14, a block diagram illustrating predictive pump controller 1104 in greater detail is shown, according to an exemplary embodiment. Predictive pump controller 1104 is shown to include a communications interface 1402 and a processing circuit 1404. Communications interface 1402 may facilitate communications between controller 1104 and external systems or devices. For example, communications interface 1402 may receive measurements of the fluid flow *Flow* from flow sensors 1416, measurements of the differential pressure *DP* across pump 1132 from pressure sensors 1418, and measurements of the power usage of pump 1132. In some embodiments, communications interface 1402 receives measurements of the state-of-charge (SOC) of battery unit 1102, which can be provided as a percentage of the maximum battery capacity (i.e., battery %). Communications interface 1402 can receive weather forecasts from a weather service 916 and predicted energy costs and demand costs from an electric utility 1318. In some embodiments, predictive pump controller 1104 uses communications interface 1402 to provide control signals pump 1132 and power inverter 1310.

[0175] Communications interface 1402 may include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications external systems or devices. In various embodiments, the communications may be direct (e.g., local wired or wireless communications) or via a communications network (e.g., a WAN, the Internet, a cellular network, etc.). For example, communications interface 1402 can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, communications interface 1402 can include a Wi-Fi transceiver for communicating via a wireless communications network or cellular or mobile phone communications transceivers.

[0176] Processing circuit 1404 is shown to include a processor 1406 and memory 1408. Processor 1406 may be a general purpose or specific purpose processor, an application

specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Processor 1406 is configured to execute computer code or instructions stored in memory 1408 or received from other computer readable media (e.g., CDROM, network storage, a remote server, etc.).

[0177] Memory 1408 may include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory 1408 may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory 1408 may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. Memory 1408 may be communicably connected to processor 1406 via processing circuit 1404 and may include computer code for executing (e.g., by processor 1406) one or more processes described herein. When processor 1406 executes instructions stored in memory 1408 for completing the various activities described herein, processor 1406 generally configures controller 1104 (and more particularly processing circuit 1404) to complete such activities.

[0178] Still referring to FIG. 14, predictive pump controller 1104 is shown to include an economic controller 1410, a tracking controller 1412, and an equipment controller 1414. Controllers 1410-1414 can be configured to perform a multi-state optimization process to generate control signals for power inverter 1310 and pump 1132. In brief overview, economic controller 1410 can optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 1314 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1102 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by pump 1132 (i.e., a pump power setpoint $P_{sp,pump}$) at each time step of an optimization period. Tracking controller 1412 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,pump}$ to determine optimal flow setpoints $Flow_{sp}$, pressure setpoints DP_{sp} , and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). Equipment controller 1414 can use the optimal setpoints $Flow_{sp}$ and/or DP_{sp} to generate control signals for pump 1132 that drive the actual

(e.g., measured) flowrate $Flow$ and/or pressure DP to the setpoints (e.g., using a feedback control technique). Each of controllers 1410-1414 is described in detail below.

Economic Controller

[0179] Economic controller 1410 can be configured to optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 1314 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1102 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by pump 1132 (i.e., a pump power setpoint $P_{sp,pump}$) at each time step of an optimization period. An example of a predictive cost function which can be optimized by economic controller 1410 is shown in the following equation:

$$\min(J) = \sum_{k=1}^h C_{ec}(k)P_{pump}(k)\Delta t + C_{DC} \max_k(P_{grid}(k)) - \sum_{k=1}^h C_{ec}(k)P_{bat}(k)\Delta t$$

where $C_{ec}(k)$ is the cost per unit of electricity (e.g., \$/kWh) purchased from electric utility 1318 during time step k , $P_{pump}(k)$ is the power consumption of pump 1132 at time step k , C_{DC} is the demand charge rate (e.g., \$/kW), where the $\max()$ term selects the maximum electricity purchase of pump unit 1100 (i.e., the maximum value of $P_{grid}(k)$) during any time step k of the optimization period, $P_{bat}(k)$ is the amount of power discharged from battery unit 1102 during time step k , and Δt is the duration of each time step k . Economic controller 1410 can optimize the predictive cost function J over the duration of the optimization period (e.g., from time step $k = 1$ to time step $k = h$) to predict the total cost of operating pump unit 1100 over the duration of the optimization period.

[0180] The first term of the predictive cost function J represents the cost of electricity consumed by pump 1132 over the duration of the optimization period. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 1318. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{pump}(k)$ is a decision variable which can be optimized by economic controller 1410.

[0181] The second term of the predictive cost function J represents the demand charge. Demand charge is an additional charge imposed by some utility providers based on the maximum power consumption during an applicable demand charge period. For example, the

demand charge rate C_{DC} may be specified in terms of dollars per unit of power (e.g., \$/kW) and may be multiplied by the peak power usage (e.g., kW) during a demand charge period to calculate the demand charge. In the predictive cost function J , the demand charge rate C_{DC} may be defined by the demand cost information received from electric utility 1318. The variable $P_{grid}(k)$ is a decision variable which can be optimized by economic controller 1410 in order to reduce the peak power usage $\max(P_{grid}(k))$ that occurs during the demand charge period. Load shifting may allow economic controller 1410 to smooth momentary spikes in the electric demand of pump unit 1100 by storing energy in battery unit 1102 when the power consumption of pump 1132 is low. The stored energy can be discharged from battery unit 1102 when the power consumption of pump 1132 is high in order to reduce the peak power draw P_{grid} from energy grid 1314, thereby decreasing the demand charge incurred.

[0182] The final term of the predictive cost function J represents the cost savings resulting from the use of battery unit 1102. Unlike the previous terms in the cost function J , the final term subtracts from the total cost. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 1318. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{bat}(k)$ is a decision variable which can be optimized by economic controller 1410. A positive value of $P_{bat}(k)$ indicates that battery unit 1102 is discharging, whereas a negative value of $P_{bat}(k)$ indicates that battery unit 1102 is charging. The power discharged from battery unit 1102 $P_{bat}(k)$ can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of pump 1132, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 1314 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k)$). However, charging battery unit 1102 results in a negative value of $P_{bat}(k)$ which adds to the total amount of power $P_{grid}(k)$ purchased from energy grid 1314.

[0183] Economic controller 1410 can optimize the predictive cost function J over the duration of the optimization period to determine optimal values of the decision variables at each time step during the optimization period. In some embodiments, the optimization period has a duration of approximately one day and each time step is approximately fifteen minutes. However, the durations of the optimization period and the time steps can vary in other embodiments and can be adjusted by a user. Advantageously, economic controller 1410 can use battery unit 1102 to perform load shifting by drawing electricity from energy grid 1314 when energy prices are low and/or when the power consumed by pump 1132 is low. The

electricity can be stored in battery unit 1102 and discharged later when energy prices are high and/or the power consumption of pump 1132 is high. This enables economic controller 1410 to reduce the cost of electricity consumed by pump unit 1100 and can smooth momentary spikes in the electric demand of pump unit 1100, thereby reducing the demand charge incurred.

[0184] Economic controller 1410 can be configured to impose constraints on the optimization of the predictive cost function J . In some embodiments, the constraints include constraints on the flow rate $Flow$ and/or differential pressure DP produced by pump 1132. Economic controller 1410 can be configured to maintain the actual or predicted flow rate $Flow$ between a minimum flow bound $Flow_{min}$ and a maximum flow bound $Flow_{max}$ (i.e., $Flow_{min} \leq Flow \leq Flow_{max}$) at all times. The parameters $Flow_{min}$ and $Flow_{max}$ may be time-varying to define different flow ranges at different times. Similarly, economic controller 1410 can be configured to maintain the actual or predicted pressure DP between a minimum pressure bound DP_{min} and a maximum pressure bound DP_{max} (i.e., $DP_{min} \leq DP \leq DP_{max}$) at all times. The parameters DP_{min} and DP_{max} may be time-varying to define different flow ranges at different times.

[0185] In addition to constraints on the fluid flowrate $Flow$ and the differential pressure DP , economic controller 1410 can impose constraints on the state-of-charge (SOC) and charge/discharge rates of battery unit 1102. In some embodiments, economic controller 1410 generates and imposes the following power constraints on the predictive cost function J :

$$\begin{aligned} P_{bat} &\leq P_{rated} \\ -P_{bat} &\leq P_{rated} \end{aligned}$$

where P_{bat} is the amount of power discharged from battery unit 1102 and P_{rated} is the rated battery power of battery unit 1102 (e.g., the maximum rate at which battery unit 1102 can be charged or discharged). These power constraints ensure that battery unit 1102 is not charged or discharged at a rate that exceeds the maximum possible battery charge/discharge rate P_{rated} .

[0186] In some embodiments, economic controller 1410 generates and imposes one or more capacity constraints on the predictive cost function J . The capacity constraints may be used to relate the battery power P_{bat} charged or discharged during each time step to the capacity and SOC of battery unit 1102. The capacity constraints may ensure that the capacity of battery

unit 1102 is maintained within acceptable lower and upper bounds at each time step of the optimization period. In some embodiments, economic controller 1410 generates the following capacity constraints:

$$\begin{aligned} C_a(k) - P_{bat}(k)\Delta t &\leq C_{rated} \\ C_a(k) - P_{bat}(k)\Delta t &\geq 0 \end{aligned}$$

where $C_a(k)$ is the available battery capacity (e.g., kWh) at the beginning of time step k , $P_{bat}(k)$ is the rate at which battery unit 1102 is discharged during time step k (e.g., kW), Δt is the duration of each time step, and C_{rated} is the maximum rated capacity of battery unit 1102 (e.g., kWh). The term $P_{bat}(k)\Delta t$ represents the change in battery capacity during time step k . These capacity constraints ensure that the capacity of battery unit 1102 is maintained between zero and the maximum rated capacity C_{rated} .

[0187] In some embodiments, economic controller 1410 generates and imposes one or more capacity constraints on the operation of pump 1132. For example, pump 1132 may have a maximum operating point (e.g., a maximum pump speed, a maximum differential pressure, etc.) which corresponds to a maximum power consumption $P_{pump,max}$. Economic controller 1410 can be configured to generate a constraint which limits the power P_{pump} provided to pump 1132 between zero and the maximum power consumption $P_{pump,max}$ as shown in the following equation:

$$\begin{aligned} 0 &\leq P_{pump} \leq P_{pump,max} \\ P_{pump} &= P_{sp,grid} + P_{sp,bat} \end{aligned}$$

where the total power P_{pump} provided to pump 1132 is the sum of the grid power setpoint $P_{sp,grid}$ and the battery power setpoint $P_{sp,bat}$.

[0188] Economic controller 1410 can optimize the predictive cost function J subject to the constraints to determine optimal values for the decision variables P_{pump} , P_{grid} , and P_{bat} , where $P_{pump} = P_{bat} + P_{grid}$. In some embodiments, economic controller 1410 uses the optimal values for P_{pump} , P_{bat} , and/or P_{grid} to generate power setpoints for tracking controller 1412. The power setpoints can include battery power setpoints $P_{sp,bat}$, grid power setpoints $P_{sp,grid}$, and/or pump power setpoints $P_{sp,pump}$ for each of the time steps k in the optimization period. Economic controller 1410 can provide the power setpoints to tracking controller 1412.

Tracking Controller

[0189] Tracking controller 1412 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,pump}$ generated by economic controller 1410 to determine optimal flow setpoints $Flow_{sp}$, optimal pressure setpoints DP_{sp} , and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). In some embodiments, tracking controller 1412 generates a flow setpoint $Flow_{sp}$ and/or a pressure setpoint DP_{sp} that are predicted to achieve the power setpoint $P_{sp,pump}$ for pump 1132. In other words, tracking controller 1412 may generate a flow setpoint $Flow_{sp}$ and/or a pressure setpoint DP_{sp} that cause pump 1132 to consume the optimal amount of power P_{pump} determined by economic controller 1410.

[0190] In some embodiments, tracking controller 1412 uses the battery power setpoint $P_{sp,bat}$ to determine the optimal rate $Bat_{C/D}$ at which to charge or discharge battery unit 1102. For example, the battery power setpoint $P_{sp,bat}$ may define a power value (kW) which can be translated by tracking controller 1412 into a control signal for power inverter 1310 and/or equipment controller 1414. In other embodiments, the battery power setpoint $P_{sp,bat}$ is provided directly to power inverter 1310 and used by power inverter 1310 to control the battery power P_{bat} .

Equipment Controller

[0191] Equipment controller 1414 can use the optimal flow setpoints $Flow_{sp}$ and/or a pressure setpoints DP_{sp} generated by tracking controller 1412 to generate control signals for pump 1132. The control signals generated by equipment controller 1414 may drive the actual (e.g., measured) flow rate $Flow$ and pressure DP to the setpoints. Equipment controller 1414 can use any of a variety of control techniques to generate control signals for pump 1132. For example, equipment controller 1414 can use state-based algorithms, extremum seeking control (ESC) algorithms, proportional-integral (PI) control algorithms, proportional-integral-derivative (PID) control algorithms, model predictive control (MPC) algorithms, or other feedback control algorithms, to generate control signals for pump 1132.

[0192] The control signals may include on/off commands, speed commands for pump 1132, power commands for pump 1132, or other types of operating commands for pump 1132. In other embodiments, the control signals may include the flow setpoints $Flow_{sp}$ and/or a pressure setpoints DP_{sp} generated by predictive pump controller 1104. The setpoints can be

provided to pump 1132 or a local controller for pump 1132 which operate to achieve the setpoints. For example, a local controller for pump 1132 may receive a measurement of the fluid flowrate $Flow$ from flow sensors 1416 and/or a measurement the differential pressure DP from pressure sensors 1418 and can modulate the speed of pump 1132 to drive the measured flowrate and/or pressure to the setpoints.

[0193] In some embodiments, equipment controller 1414 is configured to provide control signals to power inverter 1310. The control signals provided to power inverter 1310 can include a battery power setpoint $P_{sp,bat}$ and/or the optimal charge/discharge rate $Bat_{C/D}$. Equipment controller 1414 can be configured to operate power inverter 1310 to achieve the battery power setpoint $P_{sp,bat}$. For example, equipment controller 1414 can cause power inverter 1310 to charge battery unit 1102 or discharge battery unit 1102 in accordance with the battery power setpoint $P_{sp,bat}$.

Cooling Tower With Battery Unit and Predictive Control

[0194] Referring now to FIG. 15, a cooling tower system 1500 is shown, according to some embodiments. System 1500 is shown to include a cooling tower 1512 and a battery unit 1502 with a predictive cooling tower controller 1504. Cooling tower 1512 can be configured to provide cooling to a cooling load 1522. Cooling load 1522 can include, for example, a building zone, a supply airstream flowing through an air duct, an airflow in an air handling unit or rooftop unit, fluid flowing through a heat exchanger, a refrigerator or freezer, a condenser or evaporator, a cooling coil, or any other type of system, device, or space which requires cooling. In some embodiments, a pump 1516 circulates a chilled fluid to cooling load 1522 via a cooling tower circuit 1532. The chilled fluid can absorb heat from cooling load 1522, thereby providing cooling to cooling load 1522 and warming the chilled fluid.

[0195] Cooling tower 1512 can be configured to cool the water in cooling tower circuit 1532 by transferring heat from the water to outside air. Cooling tower 1512 may include a fan 1514 which causes cool air to flow through cooling tower 1512. Cooling tower 1512 places the cool air in a heat exchange relationship with the warmer water, thereby transferring heat from warmer water to the cooler air. Although cooling tower circuit 1532 is shown and described as circulating water, it should be understood that any type of coolant or working fluid (e.g., water, glycol, CO_2 , etc.) can be used in cooling tower circuit 1532.

[0196] Still referring to FIG. 15, system 1500 is shown to include a battery unit 1502. In some embodiments, battery unit 1502 includes one or more photovoltaic (PV) panels 1508. PV panels 1508 may include a collection of photovoltaic cells. The photovoltaic cells are configured to convert solar energy (i.e., sunlight) into electricity using a photovoltaic material such as monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, copper indium gallium selenide/sulfide, or other materials that exhibit the photovoltaic effect. In some embodiments, the photovoltaic cells are contained within packaged assemblies that form PV panels 1508. Each PV panel 1508 may include a plurality of linked photovoltaic cells. PV panels 1508 may combine to form a photovoltaic array.

[0197] In some embodiments, PV panels 1508 are configured to maximize solar energy collection. For example, battery unit 1502 may include a solar tracker (e.g., a GPS tracker, a sunlight sensor, etc.) that adjusts the angle of PV panels 1508 so that PV panels 1508 are aimed directly at the sun throughout the day. The solar tracker may allow PV panels 1508 to receive direct sunlight for a greater portion of the day and may increase the total amount of power produced by PV panels 1508. In some embodiments, battery unit 1502 includes a collection of mirrors, lenses, or solar concentrators configured to direct and/or concentrate sunlight on PV panels 1508. The energy generated by PV panels 1508 may be stored in battery cells 1506 and/or used to power various components of cooling tower 1512.

[0198] In some embodiments, battery unit 1502 includes one or more battery cells 1506. Battery cells 1506 are configured to store and discharge electric energy (i.e., electricity). In some embodiments, battery unit 1502 is charged using electricity from an external energy grid (e.g., provided by an electric utility). The electricity stored in battery unit 1502 can be discharged to power one or more powered components of cooling tower 1512 (e.g., fan 1514, pump 1516, etc.). Advantageously, battery unit 1502 allows cooling tower 1512 to draw electricity from the energy grid and charge battery unit 1502 when energy prices are low and discharge the stored electricity when energy prices are high to time-shift the electric load of cooling tower 1512. In some embodiments, battery unit 1502 has sufficient energy capacity to power cooling tower 1512 for approximately 4-6 hours when operating at maximum capacity such that battery unit 1502 can be utilized during high energy cost periods and charged during low energy cost periods.

[0199] In some embodiments, predictive cooling tower controller 1504 performs an optimization process to determine whether to charge or discharge battery unit 1502 during

each of a plurality of time steps that occur during an optimization period. Predictive cooling tower controller 1504 may use weather and pricing data 1510 to predict the amount of heating/cooling required and the cost of electricity during each of the plurality of time steps. Predictive cooling tower controller 1504 can optimize an objective function that accounts for the cost of electricity purchased from the energy grid over the duration of the optimization period. In some embodiments, the objective function also accounts for the cost of operating various components of cooling tower 1512 (e.g., cost of natural gas used to fuel boilers). Predictive cooling tower controller 1504 can determine an amount of electricity to purchase from the energy grid and an amount of electricity to store or discharge from battery unit 1502 during each time step. The objective function and the optimization performed by predictive cooling tower controller 1504 are described in greater detail with reference to FIGS. 16-17.

Predictive Cooling Tower Control System

[0200] Referring now to FIG. 16, a block diagram of a predictive cooling tower control system 1600 is shown, according to some embodiments. Several of the components shown in control system 1600 may be part of cooling tower 1512. For example, cooling tower 1512 may include powered cooling tower components 1602, battery unit 1502, predictive cooling tower controller 1504, power inverter 1610, and a power junction 1612. Powered cooling tower components 1602 may include any component of cooling tower 1512 that consumes power (e.g., electricity) during operation. For example, powered cooling tower components 1602 are shown to include cooling fan 1514 and pump 1516.

[0201] Power inverter 1610 may be configured to convert electric power between direct current (DC) and alternating current (AC). For example, battery unit 1502 may be configured to store and output DC power, whereas energy grid 1614 and powered cooling tower components 1602 may be configured to consume and provide AC power. Power inverter 1610 may be used to convert DC power from battery unit 1502 into a sinusoidal AC output synchronized to the grid frequency of energy grid 1614 and/or powered cooling tower components 1602. Power inverter 1610 may also be used to convert AC power from energy grid 1614 into DC power that can be stored in battery unit 1502. The power output of battery unit 1502 is shown as P_{bat} . P_{bat} may be positive if battery unit 1502 is providing power to power inverter 1610 (i.e., battery unit 1502 is discharging) or negative if battery unit 1502 is receiving power from power inverter 1610 (i.e., battery unit 1502 is charging).

[0202] In some instances, power inverter 1610 receives a DC power output from battery unit 1502 and converts the DC power output to an AC power output that can be provided to powered cooling tower components 1602. Power inverter 1610 may synchronize the frequency of the AC power output with that of energy grid 1614 (e.g., 50 Hz or 60 Hz) using a local oscillator and may limit the voltage of the AC power output to no higher than the grid voltage. In some embodiments, power inverter 1610 is a resonant inverter that includes or uses LC circuits to remove the harmonics from a simple square wave in order to achieve a sine wave matching the frequency of energy grid 1614. In various embodiments, power inverter 1610 may operate using high-frequency transformers, low-frequency transformers, or without transformers. Low-frequency transformers may convert the DC output from battery unit 1502 directly to the AC output provided to powered cooling tower components 1602. High-frequency transformers may employ a multi-step process that involves converting the DC output to high-frequency AC, then back to DC, and then finally to the AC output provided to powered cooling tower components 1602.

[0203] The power output of PV panels 1508 is shown as P_{PV} . The power output P_{PV} of PV panels 1508 can be stored in battery unit 1502 and/or used to power powered cooling tower components 1602. In some embodiments, PV panels 1508 measure the amount of power P_{PV} generated by PV panels 1508 and provides an indication of the PV power to predictive cooling tower controller 1504. For example, PV panels 1508 are shown providing an indication of the PV power percentage (i.e., PV %) to predictive cooling tower controller 1504. The PV power percentage may represent a percentage of the maximum PV power at which PV panels 1508 are currently operating.

[0204] Power junction 1612 is the point at which powered cooling tower components 1602, energy grid 1614, PV panels 1508, and power inverter 1610 are electrically connected. The power supplied to power junction 1612 from power inverter 1610 is shown as P_{bat} . P_{bat} may be positive if power inverter 1610 is providing power to power junction 1612 (i.e., battery unit 1502 is discharging) or negative if power inverter 1610 is receiving power from power junction 1612 (i.e., battery unit 1502 is charging). The power supplied to power junction 1612 from energy grid 1614 is shown as P_{grid} and the power supplied to power junction 1612 from PV panels 1508 is shown as P_{PV} . P_{bat} , P_{PV} , and P_{grid} combine at power junction 1612 to form P_{total} (i.e., $P_{total} = P_{grid} + P_{bat} + P_{PV}$). P_{total} may be defined as the power provided to powered cooling tower components 1602 from power junction 1612. In some

instances, P_{total} is greater than P_{grid} . For example, when battery unit 1502 is discharging, P_{bat} may be positive which adds to the grid power P_{grid} and the PV power P_{PV} when P_{bat} and P_{PV} combine with P_{grid} to form P_{total} . In other instances, P_{total} may be less than P_{grid} . For example, when battery unit 1502 is charging, P_{bat} may be negative which subtracts from the grid power P_{grid} and the PV power P_{PV} when P_{bat} , P_{PV} , and P_{grid} combine to form P_{total} .

[0205] Predictive cooling tower controller 1504 can be configured to control powered cooling tower components 1602 and power inverter 1610. In some embodiments, predictive cooling tower controller 1504 generates and provides a battery power setpoint $P_{sp,bat}$ to power inverter 1610. The battery power setpoint $P_{sp,bat}$ may include a positive or negative power value (e.g., kW) which causes power inverter 1610 to charge battery unit 1502 (when $P_{sp,bat}$ is negative) using power available at power junction 1612 or discharge battery unit 1502 (when $P_{sp,bat}$ is positive) to provide power to power junction 1612 in order to achieve the battery power setpoint $P_{sp,bat}$.

[0206] In some embodiments, predictive cooling tower controller 1504 generates and provides control signals to powered cooling tower components 1602. Predictive cooling tower controller 1504 may use a multi-stage optimization technique to generate the control signals. For example, predictive cooling tower controller 1504 may include an economic controller configured to determine the optimal amount of power to be consumed by powered cooling tower components 1602 at each time step during the optimization period. The optimal amount of power to be consumed may minimize a cost function that accounts for the cost of energy consumed by cooling tower 1512. The cost of energy may be based on time-varying energy prices from electric utility 1618. In some embodiments, predictive cooling tower controller 1504 determines an optimal amount of power to purchase from energy grid 1614 (i.e., a grid power setpoint $P_{sp,grid}$) and an optimal amount of power to store or discharge from battery unit 1502 (i.e., a battery power setpoint $P_{sp,bat}$) at each of the plurality of time steps. Predictive cooling tower controller 1504 may monitor the actual power usage of powered cooling tower components 1602 and may utilize the actual power usage as a feedback signal when generating the optimal power setpoints.

[0207] Predictive cooling tower controller 1504 may include a tracking controller configured to generate temperature setpoints that achieve the optimal amount of power

consumption at each time step. The temperature setpoints may include, for example, a sump water temperature setpoint $T_{sp,sump}$ (i.e., a temperature setpoint for the water in sump 1518) and/or a condenser water temperature setpoint $T_{sp,cond}$ (i.e., a temperature setpoint for the warm water returning to cooling tower 1512). In some embodiments, predictive cooling tower controller 1504 uses equipment models for powered cooling tower components 1602 to determine an amount of cooling that can be generated by cooling tower 1512 based on the optimal amount of power consumption.

[0208] In some embodiments, predictive cooling tower controller 1504 uses the temperature setpoints to generate the control signals for powered cooling tower components 1602. The control signals may include on/off commands, speed setpoints for fan 1514, differential pressure setpoints or flow rate setpoints for pump 1516, or other types of setpoints for individual devices of powered cooling tower components 1602. In other embodiments, the control signals may include the temperature setpoints (e.g., a sump water temperature setpoint $T_{sp,sump}$, a condenser water temperature setpoint $T_{sp,cond}$, etc.) generated by predictive cooling tower controller 1504. The temperature setpoints can be provided to powered cooling tower components 1602 or local controllers for powered cooling tower components 1602 which operate to achieve the temperature setpoints. For example, a local controller for fan 1514 may receive a measurement of the sump water temperature T_{cump} from a sump water temperature sensor and/or a measurement the condenser temperature T_{cond} from a condenser water temperature sensor. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to increase or decrease the speed of fan 1514 to drive the measured temperature(s) to the temperature setpoint(s). Similar feedback control processes can be used to control pump 1516. The multi-stage optimization performed by predictive cooling tower controller 1504 is described in greater detail with reference to FIG. 17.

Predictive Cooling Tower Controller

[0209] Referring now to FIG. 17, a block diagram illustrating predictive cooling tower controller 1504 in greater detail is shown, according to an exemplary embodiment. Predictive cooling tower controller 1504 is shown to include a communications interface 1702 and a processing circuit 1704. Communications interface 1702 may facilitate communications between controller 1504 and external systems or devices. For example, communications interface 1702 may receive measurements of the sump water temperature

T_{sump} and the condenser water temperature T_{cond} from temperature sensors 1716 and measurements of the power usage of powered cooling tower components 1602. In some embodiments, communications interface 1702 receives measurements of the state-of-charge (SOC) of battery unit 1502, which can be provided as a percentage of the maximum battery capacity (i.e., battery %). Communications interface 1702 can receive weather forecasts from a weather service 1616 and predicted energy costs and demand costs from an electric utility 1618. In some embodiments, predictive cooling tower controller 1504 uses communications interface 1702 to provide control signals powered cooling tower components 1602 and power inverter 1610.

[0210] Communications interface 1702 may include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications external systems or devices. In various embodiments, the communications may be direct (e.g., local wired or wireless communications) or via a communications network (e.g., a WAN, the Internet, a cellular network, etc.). For example, communications interface 1702 can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, communications interface 1702 can include a Wi-Fi transceiver for communicating via a wireless communications network or cellular or mobile phone communications transceivers.

[0211] Processing circuit 1704 is shown to include a processor 1706 and memory 1708. Processor 1706 may be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Processor 1706 is configured to execute computer code or instructions stored in memory 1708 or received from other computer readable media (e.g., CDRom, network storage, a remote server, etc.).

[0212] Memory 1708 may include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory 1708 may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory 1708 may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures

described in the present disclosure. Memory 1708 may be communicably connected to processor 1706 via processing circuit 1704 and may include computer code for executing (e.g., by processor 1706) one or more processes described herein. When processor 1706 executes instructions stored in memory 1708 for completing the various activities described herein, processor 1706 generally configures controller 1504 (and more particularly processing circuit 1704) to complete such activities.

[0213] Still referring to FIG. 17, predictive cooling tower controller 1504 is shown to include an economic controller 1710, a tracking controller 1712, and an equipment controller 1714. Controllers 1710-1714 can be configured to perform a multi-state optimization process to generate control signals for power inverter 1610 and powered cooling tower components 1602. In brief overview, economic controller 1710 can optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 1614 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1502 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered cooling tower components 1602 (i.e., a cooling tower power setpoint $P_{sp,total}$) at each time step of an optimization period. Tracking controller 1712 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ to determine optimal temperature setpoints (e.g., a sump water temperature setpoint $T_{sp,sump}$, a condenser water temperature setpoint $T_{sp,cond}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). Equipment controller 1714 can use the optimal temperature setpoints $T_{sp,zone}$ or $T_{sp,chw}$ to generate control signals for powered cooling tower components 1602 that drive the actual (e.g., measured) temperatures T_{zone} and/or T_{chw} to the setpoints (e.g., using a feedback control technique). Each of controllers 1710-1714 is described in detail below.

Economic Controller

[0214] Economic controller 1710 can be configured to optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 1614 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1502 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by powered cooling tower components 1602 (i.e., a cooling tower power setpoint $P_{sp,total}$) at each time step of an optimization period. An example of a predictive cost

function which can be optimized by economic controller 1710 is shown in the following equation:

$$\begin{aligned} \min(J) = & \sum_{k=1}^h C_{ec}(k)P_{fan}(k)\Delta t + \sum_{k=1}^h C_{ec}(k)P_{pump}(k)\Delta t \\ & + C_{DC} \max_k(P_{grid}(k)) - \sum_{k=1}^h C_{ec}(k)P_{bat}(k)\Delta t \end{aligned}$$

where $C_{ec}(k)$ is the cost per unit of electricity (e.g., \$/kWh) purchased from electric utility 1618 during time step k , $P_{fan}(k)$ is the power consumption (e.g., kW) of fan 1514 during time step k , $P_{pump}(k)$ is the power consumption of pump 1516 at time step k , C_{DC} is the demand charge rate (e.g., \$/kW), where the $\max(\cdot)$ term selects the maximum electricity purchase of cooling tower 1512 (i.e., the maximum value of $P_{grid}(k)$) during any time step k of the optimization period, $P_{bat}(k)$ is the amount of power discharged from battery unit 1502 during time step k , and Δt is the duration of each time step k . Economic controller 1710 can optimize the predictive cost function J over the duration of the optimization period (e.g., from time step $k = 1$ to time step $k = h$) to predict the total cost of operating cooling tower 1512 over the duration of the optimization period.

[0215] The first and second terms of the predictive cost function J represent the cost of electricity consumed by powered cooling tower components 1602 over the duration of the optimization period. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 1618. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variables $P_{fan}(k)$ and $P_{cond}(k)$ are decision variables which can be optimized by economic controller 1710. In some embodiments, the total power consumption $P_{total}(k)$ of powered cooling tower components 1602 at time step k is equal to the sum of $P_{fan}(k)$ and $P_{pump}(k)$ (i.e., $P_{total}(k) = P_{fan}(k) + P_{pump}(k)$). Accordingly, the first two terms of the predictive cost function can be replaced with the summation $\sum_{k=1}^h C_{ec}(k)P_{total}(k)\Delta t$ in some embodiments.

[0216] The third term of the predictive cost function J represents the demand charge. Demand charge is an additional charge imposed by some utility providers based on the maximum power consumption during an applicable demand charge period. For example, the demand charge rate C_{DC} may be specified in terms of dollars per unit of power (e.g., \$/kW)

and may be multiplied by the peak power usage (e.g., kW) during a demand charge period to calculate the demand charge. In the predictive cost function J , the demand charge rate C_{DC} may be defined by the demand cost information received from electric utility 1618. The variable $P_{grid}(k)$ is a decision variable which can be optimized by economic controller 1710 in order to reduce the peak power usage $\max(P_{grid}(k))$ that occurs during the demand charge period. Load shifting may allow economic controller 1710 to smooth momentary spikes in the electric demand of cooling tower 1512 by storing energy in battery unit 1502 when the power consumption of powered cooling tower components 1602 is low. The stored energy can be discharged from battery unit 1502 when the power consumption of powered cooling tower components 1602 is high in order to reduce the peak power draw P_{grid} from energy grid 1614, thereby decreasing the demand charge incurred.

[0217] The final term of the predictive cost function J represents the cost savings resulting from the use of battery unit 1502. Unlike the previous terms in the cost function J , the final term subtracts from the total cost. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 1618. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{bat}(k)$ is a decision variable which can be optimized by economic controller 1710. A positive value of $P_{bat}(k)$ indicates that battery unit 1502 is discharging, whereas a negative value of $P_{bat}(k)$ indicates that battery unit 1502 is charging. The power discharged from battery unit 1502 $P_{bat}(k)$ can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered cooling tower components 1602, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 1614 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). However, charging battery unit 1502 results in a negative value of $P_{bat}(k)$ which adds to the total amount of power $P_{grid}(k)$ purchased from energy grid 1614.

[0218] In some embodiments, the power P_{PV} provided by PV panels 1508 is not included in the predictive cost function J because generating PV power does not incur a cost. However, the power P_{PV} generated by PV panels 1508 can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of powered cooling tower components 1602, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 1614 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k) - P_{PV}(k)$). The amount of PV power P_{PV} generated during any time step k can be predicted by economic controller 1710. Several techniques for predicting the amount of PV

power generated by PV panels are described in U.S. Patent Application No. 15/247,869, U.S. Patent Application No. 15/247,844, and U.S. Patent Application No. 15/247,788. Each of these patent applications has a filing date of August 25, 2016, and the entire disclosure of each of these patent applications is incorporated by reference herein.

[0219] Economic controller 1710 can optimize the predictive cost function J over the duration of the optimization period to determine optimal values of the decision variables at each time step during the optimization period. In some embodiments, the optimization period has a duration of approximately one day and each time step is approximately fifteen minutes. However, the durations of the optimization period and the time steps can vary in other embodiments and can be adjusted by a user. Advantageously, economic controller 1710 can use battery unit 1502 to perform load shifting by drawing electricity from energy grid 1614 when energy prices are low and/or when the power consumed by powered cooling tower components 1602 is low. The electricity can be stored in battery unit 1502 and discharged later when energy prices are high and/or the power consumption of powered cooling tower components 1602 is high. This enables economic controller 1710 to reduce the cost of electricity consumed by cooling tower 1512 and can smooth momentary spikes in the electric demand of cooling tower 1512, thereby reducing the demand charge incurred.

[0220] Economic controller 1710 can be configured to impose constraints on the optimization of the predictive cost function J . In some embodiments, the constraints include constraints on the temperature T_{sump} of the sump water produced by cooling tower 1512. Economic controller 1710 can be configured to maintain the actual or predicted temperature T_{sump} between a minimum temperature bound T_{min} and a maximum temperature bound T_{max} (i.e., $T_{min} \leq T_{sump} \leq T_{max}$) at all times. Similarly, economic controller 1710 can be configured to maintain the actual or predicted temperature T_{cond} between a minimum temperature bound T_{min} and a maximum temperature bound T_{max} (i.e., $T_{min} \leq T_{cond} \leq T_{max}$) at all times. The parameters T_{min} and T_{max} may be time-varying to define different temperature ranges at different times.

[0221] In order to ensure that the temperature constraints are satisfied, economic controller 1710 can model the temperatures T_{sump} and T_{cond} as a function of the decision variables optimized by economic controller 1710. Several techniques for developing temperature models and relating temperatures to the decision variables in the predictive cost function J are described in greater detail in U.S. Patent No. 9,436,179 granted September 6, 2016, U.S.

Patent Application No. 14/694,633 filed April 23, 2015, and U.S. Patent Application No. 15/199,910 filed June 30, 2016. The entire disclosure of each of these patents and patent applications is incorporated by reference herein.

[0222] In addition to constraints on the temperature T_{sump} and T_{cond} , economic controller 1710 can impose constraints on the state-of-charge (SOC) and charge/discharge rates of battery unit 1502. In some embodiments, economic controller 1710 generates and imposes the following power constraints on the predictive cost function J :

$$\begin{aligned} P_{bat} &\leq P_{rated} \\ -P_{bat} &\leq P_{rated} \end{aligned}$$

where P_{bat} is the amount of power discharged from battery unit 1502 and P_{rated} is the rated battery power of battery unit 1502 (e.g., the maximum rate at which battery unit 1502 can be charged or discharged). These power constraints ensure that battery unit 1502 is not charged or discharged at a rate that exceeds the maximum possible battery charge/discharge rate P_{rated} .

[0223] In some embodiments, economic controller 1710 generates and imposes one or more capacity constraints on the predictive cost function J . The capacity constraints may be used to relate the battery power P_{bat} charged or discharged during each time step to the capacity and SOC of battery unit 1502. The capacity constraints may ensure that the capacity of battery unit 1502 is maintained within acceptable lower and upper bounds at each time step of the optimization period. In some embodiments, economic controller 1710 generates the following capacity constraints:

$$\begin{aligned} C_a(k) - P_{bat}(k)\Delta t &\leq C_{rated} \\ C_a(k) - P_{bat}(k)\Delta t &\geq 0 \end{aligned}$$

where $C_a(k)$ is the available battery capacity (e.g., kWh) at the beginning of time step k , $P_{bat}(k)$ is the rate at which battery unit 1502 is discharged during time step k (e.g., kW), Δt is the duration of each time step, and C_{rated} is the maximum rated capacity of battery unit 1502 (e.g., kWh). The term $P_{bat}(k)\Delta t$ represents the change in battery capacity during time step k . These capacity constraints ensure that the capacity of battery unit 1502 is maintained between zero and the maximum rated capacity C_{rated} .

[0224] In some embodiments, economic controller 1710 generates and imposes one or more capacity constraints on the operation of powered cooling tower components 1602. For

example, powered cooling tower components 1602 may have a maximum operating point (e.g., a maximum pump speed, a maximum cooling capacity, etc.) which corresponds to a maximum power consumption $P_{total,max}$. Economic controller 1710 can be configured to generate a constraint which limits the power P_{total} provided to powered cooling tower components 1602 between zero and the maximum power consumption $P_{total,max}$ as shown in the following equation:

$$0 \leq P_{total} \leq P_{total,max}$$

$$P_{total} = P_{sp,grid} + P_{sp,bat}$$

where the total power P_{total} provided to powered cooling tower components 1602 is the sum of the grid power setpoint $P_{sp,grid}$ and the battery power setpoint $P_{sp,bat}$.

[0225] Economic controller 1710 can optimize the predictive cost function J subject to the constraints to determine optimal values for the decision variables P_{total} , P_{fan} , P_{pump} , P_{grid} , and P_{bat} , where $P_{total} = P_{bat} + P_{grid} + P_{PV}$. In some embodiments, economic controller 1710 uses the optimal values for P_{total} , P_{bat} , and/or P_{grid} to generate power setpoints for tracking controller 1712. The power setpoints can include battery power setpoints $P_{sp,bat}$, grid power setpoints $P_{sp,grid}$, and/or cooling tower power setpoints $P_{sp,total}$ for each of the time steps k in the optimization period. Economic controller 1710 can provide the power setpoints to tracking controller 1712.

Tracking Controller

[0226] Tracking controller 1712 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,total}$ generated by economic controller 1710 to determine optimal temperature setpoints (e.g., a sump water temperature setpoint $T_{sp,sump}$, a condenser water temperature setpoint $T_{sp,cond}$, etc.) and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). In some embodiments, tracking controller 1712 generates a sump water temperature setpoint $T_{sp,sump}$ and/or a condenser water temperature setpoint $T_{sp,cond}$ that are predicted to achieve the power setpoint $P_{sp,total}$ for cooling tower 1512. In other words, tracking controller 1712 may generate a sump water temperature setpoint $T_{sp,sump}$ and/or a condenser water temperature setpoint $T_{sp,cond}$ that cause cooling tower 1512 to consume the optimal amount of power P_{total} determined by economic controller 1710.

[0227] In some embodiments, tracking controller 1712 relates the power consumption of cooling tower 1512 to the sump water temperature T_{sump} and the sump water temperature setpoint $T_{sp,sump}$ using a power consumption model. For example, tracking controller 1712 can use a model of equipment controller 1714 to determine the control action performed by equipment controller 1714 as a function of the sump water temperature T_{sump} and the sump water temperature setpoint $T_{sp,sump}$. An example of such a zone regulatory controller model is shown in the following equation:

$$P_{total} = f_4(T_{sump}, T_{sp,sump})$$

The function f_4 can be identified from data. For example, tracking controller 1712 can collect measurements of P_{total} and T_{sump} and identify the corresponding value of $T_{sp,sump}$. Tracking controller 1712 can perform a system identification process using the collected values of P_{total} , T_{sump} , and $T_{sp,sump}$ as training data to determine the function f_4 that defines the relationship between such variables.

[0228] Tracking controller 1712 may use a similar model to determine the relationship between the total power consumption P_{total} of cooling tower 1512 and the condenser water temperature setpoint $T_{sp,cond}$. For example, tracking controller 1712 can define the power consumption P_{total} of cooling tower 1512 as a function of the condenser water temperature T_{cond} and the condenser water temperature setpoint $T_{sp,cond}$. An example of such a model is shown in the following equation:

$$P_{total} = f_5(T_{cond}, T_{sp,cond})$$

The function f_5 can be identified from data. For example, tracking controller 1712 can collect measurements of P_{total} and T_{cond} and identify the corresponding value of $T_{sp,cond}$. Tracking controller 1712 can perform a system identification process using the collected values of P_{total} , T_{cond} , and $T_{sp,cond}$ as training data to determine the function f_5 that defines the relationship between such variables.

[0229] Tracking controller 1712 can use the relationships between P_{total} , $T_{sp,sump}$, and $T_{sp,cond}$ to determine values for $T_{sp,sump}$ and $T_{sp,cond}$. For example, tracking controller 1712 can receive the value of P_{total} as an input from economic controller 1710 (i.e., $P_{sp,total}$) and can use determine corresponding values of $T_{sp,sump}$ and $T_{sp,cond}$. Tracking controller 1712 can provide the values of $T_{sp,sump}$ and $T_{sp,cond}$ as outputs to equipment controller 1714.

[0230] In some embodiments, tracking controller 1712 uses the battery power setpoint $P_{sp,bat}$ to determine the optimal rate $Bat_{C/D}$ at which to charge or discharge battery unit 1502. For example, the battery power setpoint $P_{sp,bat}$ may define a power value (kW) which can be translated by tracking controller 1712 into a control signal for power inverter 1610 and/or equipment controller 1714. In other embodiments, the battery power setpoint $P_{sp,bat}$ is provided directly to power inverter 1610 and used by power inverter 1610 to control the battery power P_{bat} .

Equipment Controller

[0231] Equipment controller 1714 can use the optimal temperature setpoints $T_{sp,sump}$ or $T_{sp,cond}$ generated by tracking controller 1712 to generate control signals for powered cooling tower components 1602. The control signals generated by equipment controller 1714 may drive the actual (e.g., measured) temperatures T_{sump} and/or T_{cond} to the setpoints.

Equipment controller 1714 can use any of a variety of control techniques to generate control signals for powered cooling tower components 1602. For example, equipment controller 1714 can use state-based algorithms, extremum seeking control (ESC) algorithms, proportional-integral (PI) control algorithms, proportional-integral-derivative (PID) control algorithms, model predictive control (MPC) algorithms, or other feedback control algorithms, to generate control signals for powered cooling tower components 1602.

[0232] The control signals may include on/off commands, speed setpoints for fan 1514, pressure setpoints or flow rate setpoints for pump 1516, or other types of setpoints for individual devices of powered cooling tower components 1602. In other embodiments, the control signals may include the temperature setpoints (e.g., a sump water temperature setpoint $T_{sp,sump}$, a condenser water temperature setpoint $T_{sp,cond}$, etc.) generated by predictive cooling tower controller 1504. The temperature setpoints can be provided to powered cooling tower components 1602 or local controllers for powered cooling tower components 1602 which operate to achieve the temperature setpoints. For example, a local controller for fan 1514 may receive a measurement of the sump water temperature T_{sump} and/or a measurement the condenser water temperature T_{cond} from temperature sensors 1716 and can modulate the speed of fan 1514 to drive the measured temperatures to the setpoints.

[0233] In some embodiments, equipment controller 1714 is configured to provide control signals to power inverter 1610. The control signals provided to power inverter 1610 can

include a battery power setpoint $P_{sp,bat}$ and/or the optimal charge/discharge rate $Bat_{C/D}$. Equipment controller 1714 can be configured to operate power inverter 1610 to achieve the battery power setpoint $P_{sp,bat}$. For example, equipment controller 1714 can cause power inverter 1610 to charge battery unit 1502 or discharge battery unit 1502 in accordance with the battery power setpoint $P_{sp,bat}$.

Valve Unit With Battery and Predictive Control

[0234] Referring now to FIGS. 18-19, a valve unit 1800 with a battery unit 1802 and predictive valve controller 1804 is shown, according to some embodiments. Valve unit 1800 can be configured to control a valve 1832 via a valve actuator 1834. Valve 1832 can be a fluid control valve configured to control the flowrate of fluid from an inlet pipe 1812 to an outlet pipe 1814. Actuator 1834 may include a motor or other powered component configured to modulate the position of valve 1832. In some embodiments, valve unit 1800 is configured to control the flow of fluid through a HVAC device 1836 via a fluid circuit 1838. HVAC device 1836 may include, for example, a heating coil or cooling coil, an air handling unit, a rooftop unit, a heat exchanger, a refrigerator or freezer, a condenser or evaporator, a cooling tower, or any other type of system or device that receives a fluid in a HVAC system.

[0235] In some embodiments, battery unit 1802 includes one or more battery cells 1806. Battery cells 1806 are configured to store and discharge electric energy (i.e., electricity). In some embodiments, battery unit 1802 is charged using electricity from an external energy grid (e.g., provided by an electric utility). The electricity stored in battery unit 1802 can be discharged to power one or more powered components of valve unit 1800 (e.g., actuator 1834). Advantageously, battery unit 1802 allows valve unit 1800 to draw electricity from the energy grid and charge battery unit 1802 when energy prices are low and discharge the stored electricity when energy prices are high to time-shift the electric load of valve unit 1800. In some embodiments, battery unit 1802 has sufficient energy capacity to power valve unit 1800 for approximately 4-6 hours when operating at maximum capacity such that battery unit 1802 can be utilized during high energy cost periods and charged during low energy cost periods.

[0236] In some embodiments, predictive valve controller 1804 performs an optimization process to determine whether to charge or discharge battery unit 1802 during each of a plurality of time steps that occur during an optimization period. Predictive valve controller 1804 may use weather and pricing data 1810 to predict the amount of heating/cooling required and the cost of electricity during each of the plurality of time steps. Predictive valve

controller 1804 can optimize an objective function that accounts for the cost of electricity purchased from the energy grid over the duration of the optimization period. Predictive valve controller 1804 can determine an amount of electricity to purchase from the energy grid and an amount of electricity to store or discharge from battery unit 1802 during each time step. The objective function and the optimization performed by predictive valve controller 1804 are described in greater detail with reference to FIGS. 20-21.

Predictive Valve Control System

[0237] Referring now to FIG. 20, a block diagram of a predictive valve control system 2000 is shown, according to some embodiments. Several of the components shown in control system 2000 may be part of valve unit 1800. For example, valve unit 1800 may include actuator 1834, battery unit 1802, predictive valve controller 1804, power inverter 2010, and a power junction 2012.

[0238] Power inverter 2010 may be configured to convert electric power between direct current (DC) and alternating current (AC). For example, battery unit 1802 may be configured to store and output DC power, whereas energy grid 2014 and actuator 1834 may be configured to consume and provide AC power. Power inverter 2010 may be used to convert DC power from battery unit 1802 into a sinusoidal AC output synchronized to the grid frequency of energy grid 2014 and/or actuator 1834. Power inverter 2010 may also be used to convert AC power from energy grid 2014 into DC power that can be stored in battery unit 1802. The power output of battery unit 1802 is shown as P_{bat} . P_{bat} may be positive if battery unit 1802 is providing power to power inverter 2010 (i.e., battery unit 1802 is discharging) or negative if battery unit 1802 is receiving power from power inverter 2010 (i.e., battery unit 1802 is charging).

[0239] In some instances, power inverter 2010 receives a DC power output from battery unit 1802 and converts the DC power output to an AC power output that can be provided to actuator 1834. Power inverter 2010 may synchronize the frequency of the AC power output with that of energy grid 2014 (e.g., 50 Hz or 60 Hz) using a local oscillator and may limit the voltage of the AC power output to no higher than the grid voltage. In some embodiments, power inverter 2010 is a resonant inverter that includes or uses LC circuits to remove the harmonics from a simple square wave in order to achieve a sine wave matching the frequency of energy grid 2014. In various embodiments, power inverter 2010 may operate using high-frequency transformers, low-frequency transformers, or without transformers. Low-

frequency transformers may convert the DC output from battery unit 1802 directly to the AC output provided to actuator 1834. High-frequency transformers may employ a multi-step process that involves converting the DC output to high-frequency AC, then back to DC, and then finally to the AC output provided to actuator 1834.

[0240] Power junction 2012 is the point at which actuator 1834, energy grid 2014, and power inverter 2010 are electrically connected. The power supplied to power junction 2012 from power inverter 2010 is shown as P_{bat} . P_{bat} may be positive if power inverter 2010 is providing power to power junction 2012 (i.e., battery unit 1802 is discharging) or negative if power inverter 2010 is receiving power from power junction 2012 (i.e., battery unit 1802 is charging). The power supplied to power junction 2012 from energy grid 2014 is shown as P_{grid} . P_{bat} and P_{grid} combine at power junction 2012 to form P_{total} (i.e., $P_{total} = P_{grid} + P_{bat}$). P_{total} may be defined as the power provided to actuator 1834 from power junction 2012. In some instances, P_{total} is greater than P_{grid} . For example, when battery unit 1802 is discharging, P_{bat} may be positive which adds to the grid power P_{grid} when P_{bat} combines with P_{grid} to form P_{total} . In other instances, P_{total} may be less than P_{grid} . For example, when battery unit 1802 is charging, P_{bat} may be negative which subtracts from the grid power P_{grid} when P_{bat} and P_{grid} combine to form P_{total} .

[0241] Predictive valve controller 1804 can be configured to control actuator 1834 and power inverter 2010. In some embodiments, predictive valve controller 1804 generates and provides a battery power setpoint $P_{sp,bat}$ to power inverter 2010. The battery power setpoint $P_{sp,bat}$ may include a positive or negative power value (e.g., kW) which causes power inverter 2010 to charge battery unit 1802 (when $P_{sp,bat}$ is negative) using power available at power junction 2012 or discharge battery unit 1802 (when $P_{sp,bat}$ is positive) to provide power to power junction 2012 in order to achieve the battery power setpoint $P_{sp,bat}$.

[0242] In some embodiments, predictive valve controller 1804 generates and provides control signals to actuator 1834. Predictive valve controller 1804 may use a multi-stage optimization technique to generate the control signals. For example, predictive valve controller 1804 may include an economic controller configured to determine the optimal amount of power to be consumed by actuator 1834 at each time step during the optimization period. The optimal amount of power to be consumed may minimize a cost function that accounts for the cost of energy consumed by valve unit 1800. The cost of energy may be

based on time-varying energy prices from electric utility 2018. In some embodiments, predictive valve controller 1804 determines an optimal amount of power to purchase from energy grid 2014 (i.e., a grid power setpoint $P_{sp,grid}$) and an optimal amount of power to store or discharge from battery unit 1802 (i.e., a battery power setpoint $P_{sp,bat}$) at each of the plurality of time steps. Predictive valve controller 1804 may monitor the actual power usage of actuator 1834 and may utilize the actual power usage as a feedback signal when generating the optimal power setpoints.

[0243] Predictive valve controller 1804 may include a tracking controller configured to generate position setpoints for actuator 1834 that achieve the optimal amount of power consumption at each time step. In some embodiments, predictive valve controller 1804 uses an equipment model for actuator 1834 to determine an a position of actuator 1834 that corresponds to the optimal amount of power consumption.

[0244] In some embodiments, predictive valve controller 1804 uses the position setpoints to generate the control signals for actuator 1834. The control signals may include on/off commands, position commands, voltage signals, or other types of setpoints that affect the operation of actuator 1834. In other embodiments, the control signals may include the position setpoints generated by predictive valve controller 1804. The setpoints can be provided to actuator 1834 or local controllers for actuator 1834 which operate to achieve the setpoints. For example, a local controller for actuator 1834 may receive a measurement of the valve position from one or more position sensors. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to adjust the position of actuator 1834 and/or valve 1832 to drive the measured position to the setpoint(s). The multi-stage optimization performed by predictive valve controller 1804 is described in greater detail with reference to FIG. 21.

Predictive Valve Controller

[0245] Referring now to FIG. 21, a block diagram illustrating predictive valve controller 1804 in greater detail is shown, according to an exemplary embodiment. Predictive valve controller 1804 is shown to include a communications interface 2102 and a processing circuit 2104. Communications interface 2102 may facilitate communications between controller 1804 and external systems or devices. For example, communications interface 2102 may receive measurements of the valve position from position sensors 2118 and measurements of the power usage of actuator 1834. In some embodiments, communications interface 2102

receives measurements of the state-of-charge (SOC) of battery unit 1802, which can be provided as a percentage of the maximum battery capacity (i.e., battery %). Communications interface 2102 can receive weather forecasts from a weather service 916 and predicted energy costs and demand costs from an electric utility 2018. In some embodiments, predictive valve controller 1804 uses communications interface 2102 to provide control signals actuator 1834 and power inverter 2010.

[0246] Communications interface 2102 may include wired or wireless communications interfaces (e.g., jacks, antennas, transmitters, receivers, transceivers, wire terminals, etc.) for conducting data communications external systems or devices. In various embodiments, the communications may be direct (e.g., local wired or wireless communications) or via a communications network (e.g., a WAN, the Internet, a cellular network, etc.). For example, communications interface 2102 can include an Ethernet card and port for sending and receiving data via an Ethernet-based communications link or network. In another example, communications interface 2102 can include a Wi-Fi transceiver for communicating via a wireless communications network or cellular or mobile phone communications transceivers.

[0247] Processing circuit 2104 is shown to include a processor 2106 and memory 2108. Processor 2106 may be a general purpose or specific purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable processing components. Processor 2106 is configured to execute computer code or instructions stored in memory 2108 or received from other computer readable media (e.g., CDRom, network storage, a remote server, etc.).

[0248] Memory 2108 may include one or more devices (e.g., memory units, memory devices, storage devices, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described in the present disclosure. Memory 2108 may include random access memory (RAM), read-only memory (ROM), hard drive storage, temporary storage, non-volatile memory, flash memory, optical memory, or any other suitable memory for storing software objects and/or computer instructions. Memory 2108 may include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described in the present disclosure. Memory 2108 may be communicably connected to processor 2106 via processing circuit 2104 and may include computer code for executing (e.g., by processor 2106) one or more processes described herein. When processor 2106

executes instructions stored in memory 2108 for completing the various activities described herein, processor 2106 generally configures controller 1804 (and more particularly processing circuit 2104) to complete such activities.

[0249] Still referring to FIG. 21, predictive valve controller 1804 is shown to include an economic controller 2110, a tracking controller 2112, and an equipment controller 2114. Controllers 2110-2114 can be configured to perform a multi-state optimization process to generate control signals for power inverter 2010 and actuator 1834. In brief overview, economic controller 2110 can optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 2014 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1802 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by actuator 1834 (i.e., a pump power setpoint $P_{sp,act}$) at each time step of an optimization period. Tracking controller 2112 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,act}$ to determine optimal position setpoints Pos_{sp} for valve 1832 and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). Equipment controller 2114 can use the optimal position setpoints Pos_{sp} to generate control signals for actuator 1834 that drive the actual (e.g., measured) position to the setpoints (e.g., using a feedback control technique). Each of controllers 2110-2114 is described in detail below.

Economic Controller

[0250] Economic controller 2110 can be configured to optimize a predictive cost function to determine an optimal amount of power to purchase from energy grid 2014 (i.e., a grid power setpoint $P_{sp,grid}$), an optimal amount of power to store or discharge from battery unit 1802 (i.e., a battery power setpoint $P_{sp,bat}$), and/or an optimal amount of power to be consumed by actuator 1834 (i.e., an actuator power setpoint $P_{sp,act}$) at each time step of an optimization period. An example of a predictive cost function which can be optimized by economic controller 2110 is shown in the following equation:

$$\min(J) = \sum_{k=1}^h C_{ec}(k)P_{act}(k)\Delta t + C_{DC} \max_k(P_{grid}(k)) - \sum_{k=1}^h C_{ec}(k)P_{bat}(k)\Delta t$$

where $C_{ec}(k)$ is the cost per unit of electricity (e.g., \$/kWh) purchased from electric utility 2018 during time step k , $P_{act}(k)$ is the power consumption of actuator 1834 at time step k ,

C_{DC} is the demand charge rate (e.g., \$/kW), where the $\max(\)$ term selects the maximum electricity purchase of valve unit 1800 (i.e., the maximum value of $P_{grid}(k)$) during any time step k of the optimization period, $P_{bat}(k)$ is the amount of power discharged from battery unit 1802 during time step k , and Δt is the duration of each time step k . Economic controller 2110 can optimize the predictive cost function J over the duration of the optimization period (e.g., from time step $k = 1$ to time step $k = h$) to predict the total cost of operating valve unit 1800 over the duration of the optimization period.

[0251] The first term of the predictive cost function J represents the cost of electricity consumed by actuator 1834 over the duration of the optimization period. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 2018. In some embodiments, the cost of electricity varies as a function of time, which results in different values of $C_{ec}(k)$ at different time steps k . The variable $P_{act}(k)$ is a decision variable which can be optimized by economic controller 2110.

[0252] The second term of the predictive cost function J represents the demand charge. Demand charge is an additional charge imposed by some utility providers based on the maximum power consumption during an applicable demand charge period. For example, the demand charge rate C_{DC} may be specified in terms of dollars per unit of power (e.g., \$/kW) and may be multiplied by the peak power usage (e.g., kW) during a demand charge period to calculate the demand charge. In the predictive cost function J , the demand charge rate C_{DC} may be defined by the demand cost information received from electric utility 2018. The variable $P_{grid}(k)$ is a decision variable which can be optimized by economic controller 2110 in order to reduce the peak power usage $\max(P_{grid}(k))$ that occurs during the demand charge period. Load shifting may allow economic controller 2110 to smooth momentary spikes in the electric demand of valve unit 1800 by storing energy in battery unit 1802 when the power consumption of actuator 1834 is low. The stored energy can be discharged from battery unit 1802 when the power consumption of actuator 1834 is high in order to reduce the peak power draw P_{grid} from energy grid 2014, thereby decreasing the demand charge incurred.

[0253] The final term of the predictive cost function J represents the cost savings resulting from the use of battery unit 1802. Unlike the previous terms in the cost function J , the final term subtracts from the total cost. The values of the parameter $C_{ec}(k)$ at each time step k can be defined by the energy cost information provided by electric utility 2018. In some embodiments, the cost of electricity varies as a function of time, which results in different

values of $C_{ec}(k)$ at different time steps k . The variable $P_{bat}(k)$ is a decision variable which can be optimized by economic controller 2110. A positive value of $P_{bat}(k)$ indicates that battery unit 1802 is discharging, whereas a negative value of $P_{bat}(k)$ indicates that battery unit 1802 is charging. The power discharged from battery unit 1802 $P_{bat}(k)$ can be used to satisfy some or all of the total power consumption $P_{total}(k)$ of actuator 1834, which reduces the amount of power $P_{grid}(k)$ purchased from energy grid 2014 (i.e., $P_{grid}(k) = P_{total}(k) - P_{bat}(k)$). However, charging battery unit 1802 results in a negative value of $P_{bat}(k)$ which adds to the total amount of power $P_{grid}(k)$ purchased from energy grid 2014.

[0254] Economic controller 2110 can optimize the predictive cost function J over the duration of the optimization period to determine optimal values of the decision variables at each time step during the optimization period. In some embodiments, the optimization period has a duration of approximately one day and each time step is approximately fifteen minutes. However, the durations of the optimization period and the time steps can vary in other embodiments and can be adjusted by a user. Advantageously, economic controller 2110 can use battery unit 1802 to perform load shifting by drawing electricity from energy grid 2014 when energy prices are low and/or when the power consumed by actuator 1834 is low. The electricity can be stored in battery unit 1802 and discharged later when energy prices are high and/or the power consumption of actuator 1834 is high. This enables economic controller 2110 to reduce the cost of electricity consumed by valve unit 1800 and can smooth momentary spikes in the electric demand of valve unit 1800, thereby reducing the demand charge incurred.

[0255] Economic controller 2110 can be configured to impose constraints on the optimization of the predictive cost function J . In some embodiments, the constraints include constraints on the position of actuator 1834. Economic controller 2110 can be configured to maintain the actual or predicted position between a minimum position bound Pos_{min} and a maximum position bound Pos_{max} (i.e., $Pos_{min} \leq Pos \leq Pos_{max}$) at all times. The parameters Pos_{min} and Pos_{max} may be time-varying to define different position ranges at different times.

[0256] In addition to constraints on the position of valve 1832, economic controller 2110 can impose constraints on the state-of-charge (SOC) and charge/discharge rates of battery unit 1802. In some embodiments, economic controller 2110 generates and imposes the following power constraints on the predictive cost function J :

$$P_{bat} \leq P_{rated}$$

$$-P_{bat} \leq P_{rated}$$

where P_{bat} is the amount of power discharged from battery unit 1802 and P_{rated} is the rated battery power of battery unit 1802 (e.g., the maximum rate at which battery unit 1802 can be charged or discharged). These power constraints ensure that battery unit 1802 is not charged or discharged at a rate that exceeds the maximum possible battery charge/discharge rate P_{rated} .

[0257] In some embodiments, economic controller 2110 generates and imposes one or more capacity constraints on the predictive cost function J . The capacity constraints may be used to relate the battery power P_{bat} charged or discharged during each time step to the capacity and SOC of battery unit 1802. The capacity constraints may ensure that the capacity of battery unit 1802 is maintained within acceptable lower and upper bounds at each time step of the optimization period. In some embodiments, economic controller 2110 generates the following capacity constraints:

$$C_a(k) - P_{bat}(k)\Delta t \leq C_{rated}$$

$$C_a(k) - P_{bat}(k)\Delta t \geq 0$$

where $C_a(k)$ is the available battery capacity (e.g., kWh) at the beginning of time step k , $P_{bat}(k)$ is the rate at which battery unit 1802 is discharged during time step k (e.g., kW), Δt is the duration of each time step, and C_{rated} is the maximum rated capacity of battery unit 1802 (e.g., kWh). The term $P_{bat}(k)\Delta t$ represents the change in battery capacity during time step k . These capacity constraints ensure that the capacity of battery unit 1802 is maintained between zero and the maximum rated capacity C_{rated} .

[0258] In some embodiments, economic controller 2110 generates and imposes one or more capacity constraints on the operation of actuator 1834. For example, actuator 1834 may have a maximum operating point (e.g., a maximum actuation speed, a maximum position, etc.) which corresponds to a maximum power consumption $P_{act,max}$. Economic controller 2110 can be configured to generate a constraint which limits the power P_{act} provided to actuator 1834 between zero and the maximum power consumption $P_{act,max}$ as shown in the following equation:

$$0 \leq P_{act} \leq P_{act,max}$$

$$P_{act} = P_{sp,grid} + P_{sp,bat}$$

where the total power P_{act} provided to actuator 1834 is the sum of the grid power setpoint $P_{sp,grid}$ and the battery power setpoint $P_{sp,bat}$.

[0259] Economic controller 2110 can optimize the predictive cost function J subject to the constraints to determine optimal values for the decision variables P_{act} , P_{grid} , and P_{bat} , where $P_{act} = P_{bat} + P_{grid}$. In some embodiments, economic controller 2110 uses the optimal values for P_{act} , P_{bat} , and/or P_{grid} to generate power setpoints for tracking controller 2112. The power setpoints can include battery power setpoints $P_{sp,bat}$, grid power setpoints $P_{sp,grid}$, and/or actuator power setpoints $P_{sp,act}$ for each of the time steps k in the optimization period. Economic controller 2110 can provide the power setpoints to tracking controller 2112.

Tracking Controller

[0260] Tracking controller 2112 can use the optimal power setpoints $P_{sp,grid}$, $P_{sp,bat}$, and/or $P_{sp,act}$ generated by economic controller 2110 to determine optimal position setpoints Pos_{sp} and an optimal battery charge or discharge rate (i.e., $Bat_{C/D}$). In some embodiments, tracking controller 2112 generates a position setpoint Pos_{sp} predicted to achieve the power setpoint $P_{sp,act}$ for actuator 1834. In other words, tracking controller 2112 may generate a position setpoint Pos_{sp} that causes actuator 1834 to consume the optimal amount of power P_{act} determined by economic controller 2110.

[0261] In some embodiments, tracking controller 2112 uses the battery power setpoint $P_{sp,bat}$ to determine the optimal rate $Bat_{C/D}$ at which to charge or discharge battery unit 1802. For example, the battery power setpoint $P_{sp,bat}$ may define a power value (kW) which can be translated by tracking controller 2112 into a control signal for power inverter 2010 and/or equipment controller 2114. In other embodiments, the battery power setpoint $P_{sp,bat}$ is provided directly to power inverter 2010 and used by power inverter 2010 to control the battery power P_{bat} .

Equipment Controller

[0262] Equipment controller 2114 can use the optimal position setpoints Pos_{sp} generated by tracking controller 2112 to generate control signals for actuator 1834. The control signals generated by equipment controller 2114 may drive the actual (e.g., measured) position of

valve 1832 the setpoints. Equipment controller 2114 can use any of a variety of control techniques to generate control signals for actuator 1834. For example, equipment controller 2114 can use state-based algorithms, extremum seeking control (ESC) algorithms, proportional-integral (PI) control algorithms, proportional-integral-derivative (PID) control algorithms, model predictive control (MPC) algorithms, or other feedback control algorithms, to generate control signals for actuator 1834.

[0263] The control signals may include on/off commands, position commands, voltage signals, or other types of setpoints that affect the operation of actuator 1834. In other embodiments, the control signals may include the position setpoints generated by predictive valve controller 1804. The setpoints can be provided to actuator 1834 or local controllers for actuator 1834 which operate to achieve the setpoints. For example, a local controller for actuator 1834 may receive a measurement of the valve position from one or more position sensors. The local controller can use a feedback control process (e.g., PID, ESC, MPC, etc.) to adjust the position of actuator 1834 and/or valve 1832 to drive the measured position to the setpoint.

[0264] In some embodiments, equipment controller 2114 is configured to provide control signals to power inverter 2010. The control signals provided to power inverter 2010 can include a battery power setpoint $P_{sp,bat}$ and/or the optimal charge/discharge rate $Bat_{C/D}$. Equipment controller 2114 can be configured to operate power inverter 2010 to achieve the battery power setpoint $P_{sp,bat}$. For example, equipment controller 2114 can cause power inverter 2010 to charge battery unit 1802 or discharge battery unit 1802 in accordance with the battery power setpoint $P_{sp,bat}$.

Configuration of Exemplary Embodiments

[0265] The construction and arrangement of the systems and methods as shown in the various exemplary embodiments are illustrative only. Although only a few embodiments have been described in detail in this disclosure, many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.). For example, the position of elements can be reversed or otherwise varied and the nature or number of discrete elements or positions can be altered or varied. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. The order or sequence of any process or method steps can be varied or re-sequenced according to

alternative embodiments. Other substitutions, modifications, changes, and omissions can be made in the design, operating conditions and arrangement of the exemplary embodiments without departing from the scope of the present disclosure.

[0266] The present disclosure contemplates methods, systems and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure can be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0267] Although the figures show a specific order of method steps, the order of the steps may differ from what is depicted. Also two or more steps can be performed concurrently or with partial concurrence. Such variation will depend on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations could be accomplished with standard programming techniques with rule based logic and other logic to accomplish the various connection steps, processing steps, comparison steps and decision steps.

WHAT IS CLAIMED IS:

1. A central energy facility (CEF) comprising:
 - a plurality of powered CEF components comprising a chiller unit and a cooling tower;
 - a battery unit configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered CEF components; and
 - a predictive CEF controller configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered CEF components at each time step of an optimization period.
2. The CEF of Claim 1, further comprising one or more photovoltaic panels configured to collect photovoltaic energy;
 - wherein the predictive CEF controller is configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered CEF components at each time step of the optimization period.
3. The CEF of Claim 1, wherein the predictive cost function accounts for:
 - a cost of the electric energy purchased from the energy grid at each time step of the optimization period; and
 - a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.
4. The CEF of Claim 1, wherein the predictive CEF controller is configured to:
 - receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period; and
 - use the energy pricing data as inputs to the predictive cost function.

5. The CEF of Claim 1, wherein the predictive cost function accounts for a demand charge based on a maximum power consumption of the CEF during a demand charge period that overlaps at least partially with the optimization period;

wherein the predictive CEF controller is configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

6. The CEF of Claim 1, wherein the predictive CEF controller comprises:

an economic controller configured to determine optimal power setpoints for the powered CEF components and for the battery unit at each time step of the optimization period;

a tracking controller configured to use the optimal power setpoints to determine optimal temperature setpoints at each time step of the optimization period; and

an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered CEF components and for the battery unit at each time step of the optimization period.

7. An air-cooled chiller unit comprising:

a refrigeration circuit comprising an evaporator and a condenser;

a plurality of powered chiller components comprising a compressor configured to circulate a refrigerant through the refrigeration circuit and a fan configured to provide cooling for the condenser;

a battery unit configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered chiller components; and

a predictive chiller controller configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered chiller components at each time step of an optimization period.

8. The air-cooled chiller unit of Claim 7, further comprising one or more photovoltaic panels configured to collect photovoltaic energy;

wherein the predictive chiller controller is configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered chiller components at each time step of the optimization period.

9. The air-cooled chiller unit of Claim 7, wherein the predictive cost function accounts for:

a cost of the electric energy purchased from the energy grid at each time step of the optimization period; and

a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

10. The air-cooled chiller unit of Claim 7, wherein the predictive chiller controller is configured to:

receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period; and

use the energy pricing data as inputs to the predictive cost function.

11. The air-cooled chiller unit of Claim 7, wherein the predictive cost function accounts for a demand charge based on a maximum power consumption of the air-cooled chiller unit during a demand charge period that overlaps at least partially with the optimization period;

wherein the predictive chiller controller is configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

12. The air-cooled chiller unit of Claim 7, wherein the predictive chiller controller comprises:

an economic controller configured to determine optimal power setpoints for the powered chiller components and for the battery unit at each time step of the optimization period;

a tracking controller configured to use the optimal power setpoints to determine optimal temperature setpoints at each time step of the optimization period; and

an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered chiller components and for the battery unit at each time step of the optimization period.

13. A pump unit comprising:

a pump configured to circulate a fluid through a fluid circuit;;

a battery unit configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the pump; and

a predictive pump controller configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the pump at each time step of an optimization period.

14. The pump unit of Claim 13, wherein the predictive cost function accounts for:

a cost of the electric energy purchased from the energy grid at each time step of the optimization period; and

a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.

15. The pump unit of Claim 13, wherein the predictive pump controller is configured to: receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period; and

use the energy pricing data as inputs to the predictive cost function.

16. The pump unit of Claim 13, wherein the predictive cost function accounts for a demand charge based on a maximum power consumption of the pump unit during a demand charge period that overlaps at least partially with the optimization period;

wherein the predictive pump controller is configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

17. The pump unit of Claim 13, wherein the predictive pump controller comprises:

an economic controller configured to determine optimal power setpoints for the pump and for the battery unit at each time step of the optimization period;

a tracking controller configured to use the optimal power setpoints to determine optimal flow setpoints or pressure setpoints at each time step of the optimization period; and

an equipment controller configured to use the optimal flow setpoints or pressure setpoints to generate control signals for the pump and for the battery unit at each time step of the optimization period.

18. A cooling tower unit comprising:

one or more powered cooling tower components comprising at least one of a fan and a pump;

a battery unit configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered cooling tower components; and

a predictive cooling tower controller configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered cooling tower components at each time step of an optimization period.

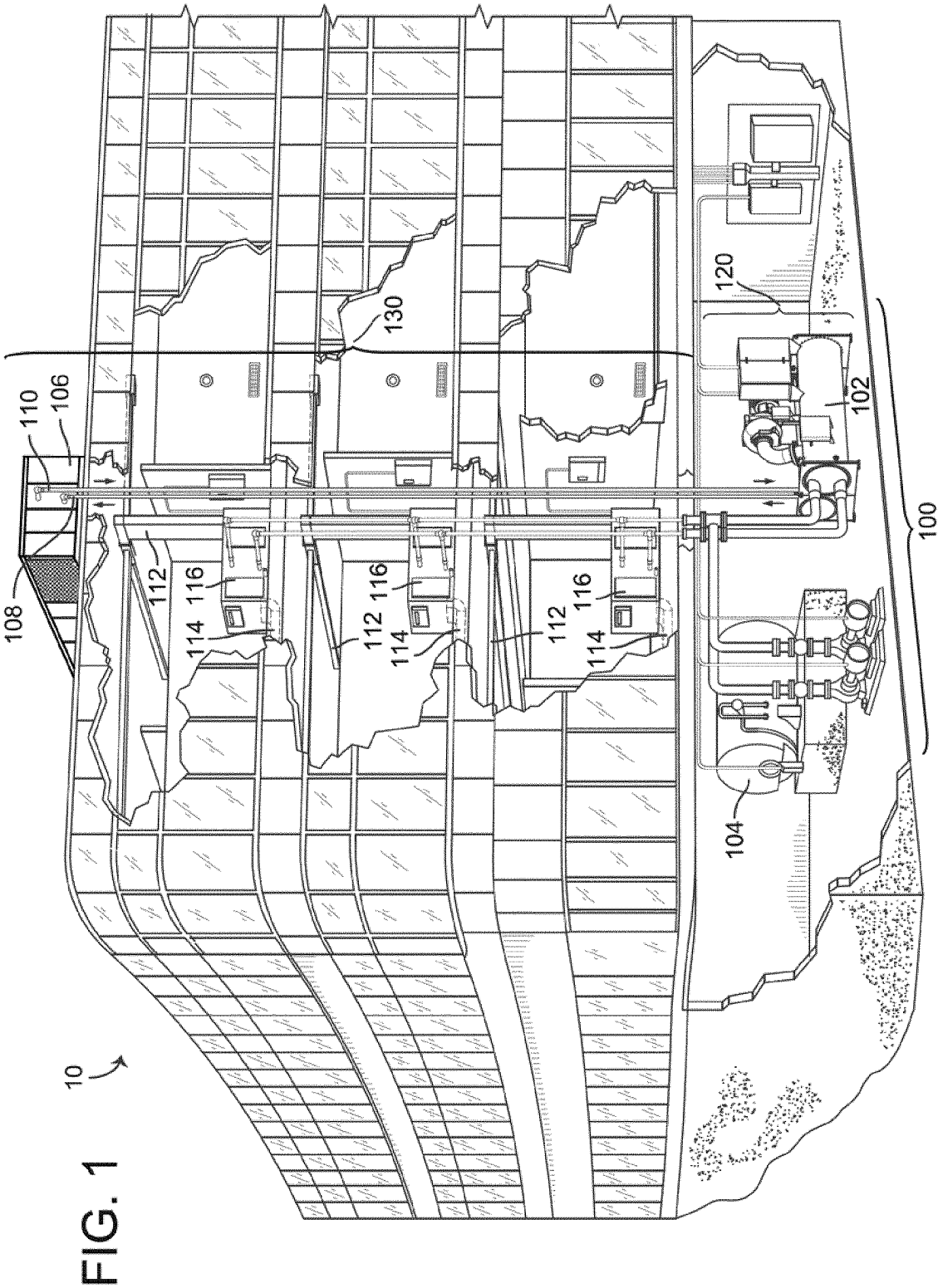
19. The cooling tower unit of Claim 18, further comprising one or more photovoltaic panels configured to collect photovoltaic energy;

wherein the predictive cooling tower controller is configured to determine an optimal amount of the photovoltaic energy to store in the battery unit and an optimal amount of the photovoltaic energy to be consumed by the powered cooling tower components at each time step of the optimization period.

20. The cooling tower unit of Claim 18, wherein the predictive cost function accounts for:
a cost of the electric energy purchased from the energy grid at each time step of the optimization period; and
a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.
21. The cooling tower unit of Claim 18, wherein the predictive cooling tower controller is configured to:
receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period; and
use the energy pricing data as inputs to the predictive cost function.
22. The cooling tower unit of Claim 18, wherein the predictive cost function accounts for a demand charge based on a maximum power consumption of the cooling tower unit during a demand charge period that overlaps at least partially with the optimization period;
wherein the predictive cooling tower controller is configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.
23. The cooling tower unit of Claim 18, wherein the predictive cooling tower controller comprises:
an economic controller configured to determine optimal power setpoints for the powered cooling tower components and for the battery unit at each time step of the optimization period;
a tracking controller configured to use the optimal power setpoints to determine optimal temperature setpoints at each time step of the optimization period; and
an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered cooling tower components and for the battery unit at each time step of the optimization period.

24. A valve unit comprising:
- a valve configured to control a flowrate of a fluid through a fluid conduit;
 - one or more powered valve components comprising a valve actuator coupled to the valve and configured to modulate a position of the valve;
 - a battery unit configured to store electric energy from an energy grid and discharge the stored electric energy for use in powering the powered valve components; and
 - a predictive valve controller configured to optimize a predictive cost function to determine an optimal amount of electric energy to purchase from the energy grid and an optimal amount of electric energy to store in the battery unit or discharge from the battery unit for use in powering the powered valve components at each time step of an optimization period.
25. The valve unit of Claim 24, wherein the predictive cost function accounts for:
- a cost of the electric energy purchased from the energy grid at each time step of the optimization period; and
 - a cost savings resulting from discharging stored electric energy from the battery unit at each time step of the optimization period.
26. The valve unit of Claim 24, wherein the predictive valve controller is configured to:
- receive energy pricing data defining a cost per unit of electric energy purchased from the energy grid at each time step of the optimization period; and
 - use the energy pricing data as inputs to the predictive cost function.
27. The valve unit of Claim 24, wherein the predictive cost function accounts for a demand charge based on a maximum power consumption of the valve unit during a demand charge period that overlaps at least partially with the optimization period;
- wherein the predictive valve controller is configured to receive energy pricing data defining the demand charge and to use the energy pricing data as inputs to the predictive cost function.

28. The valve unit of Claim 24, wherein the predictive valve controller comprises:
- an economic controller configured to determine optimal power setpoints for the powered valve components and for the battery unit at each time step of the optimization period;
 - a tracking controller configured to use the optimal power setpoints to determine optimal position setpoints at each time step of the optimization period; and
 - an equipment controller configured to use the optimal temperature setpoints to generate control signals for the powered valve components and for the battery unit at each time step of the optimization period.



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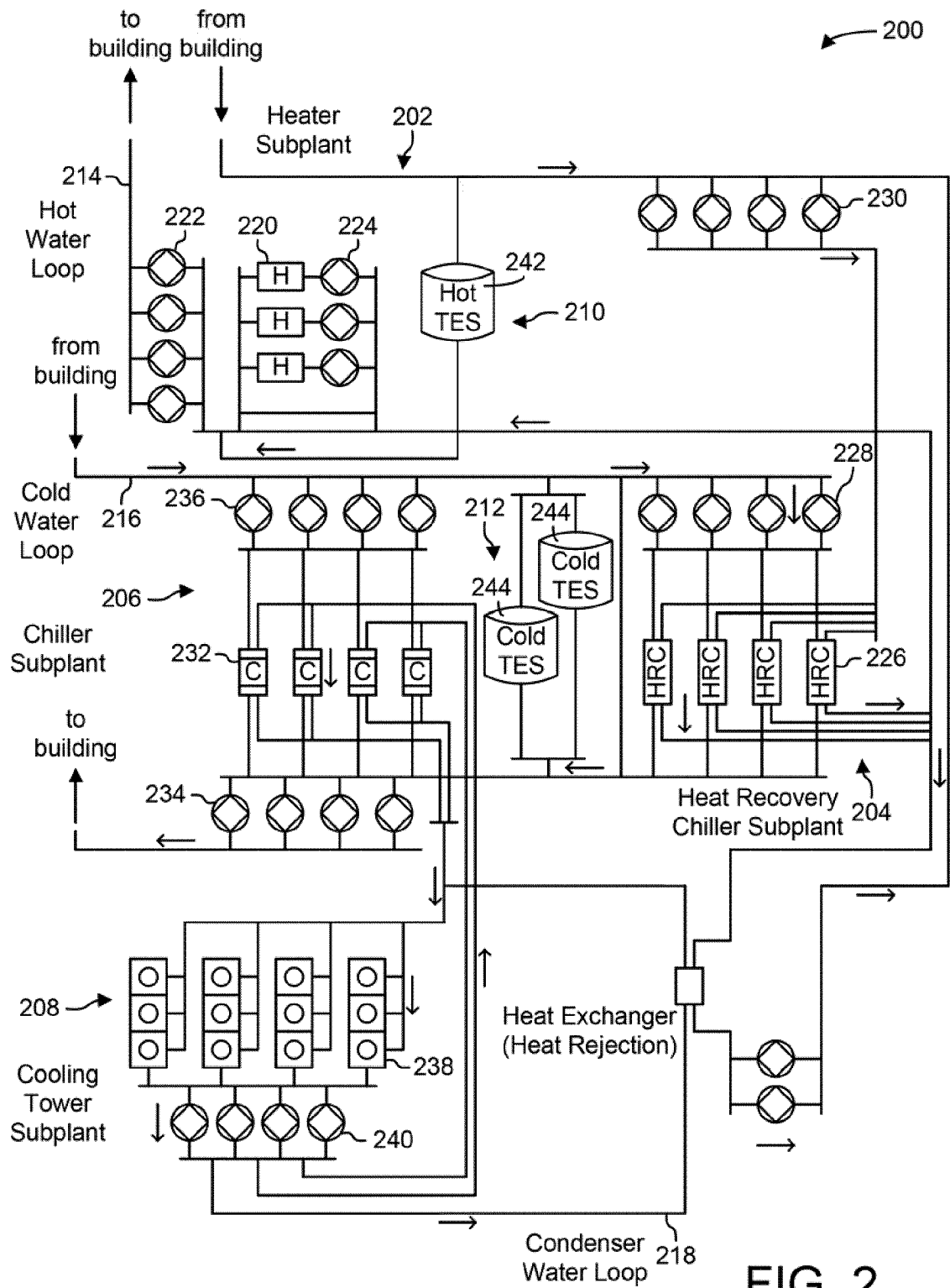


FIG. 2

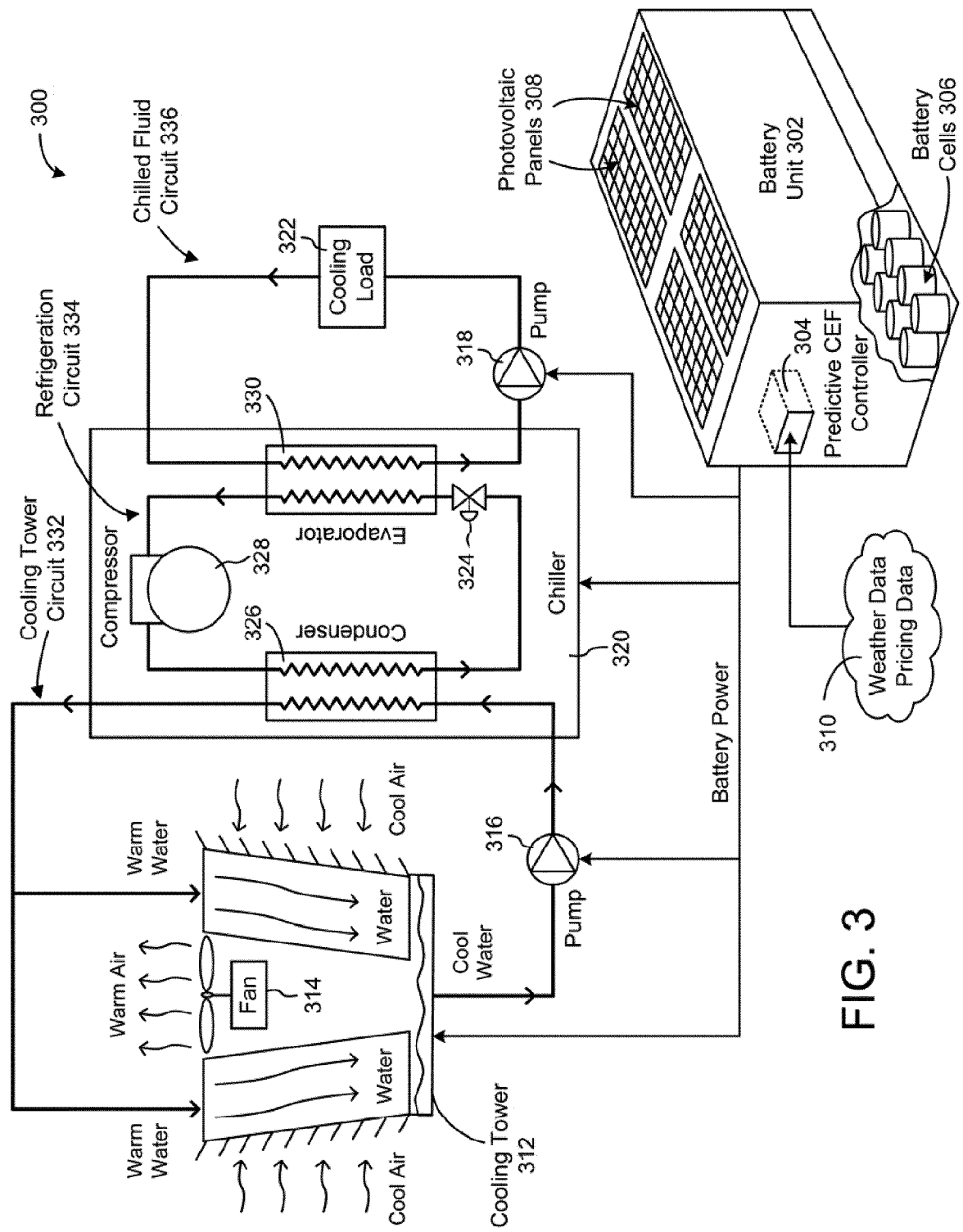


FIG. 3

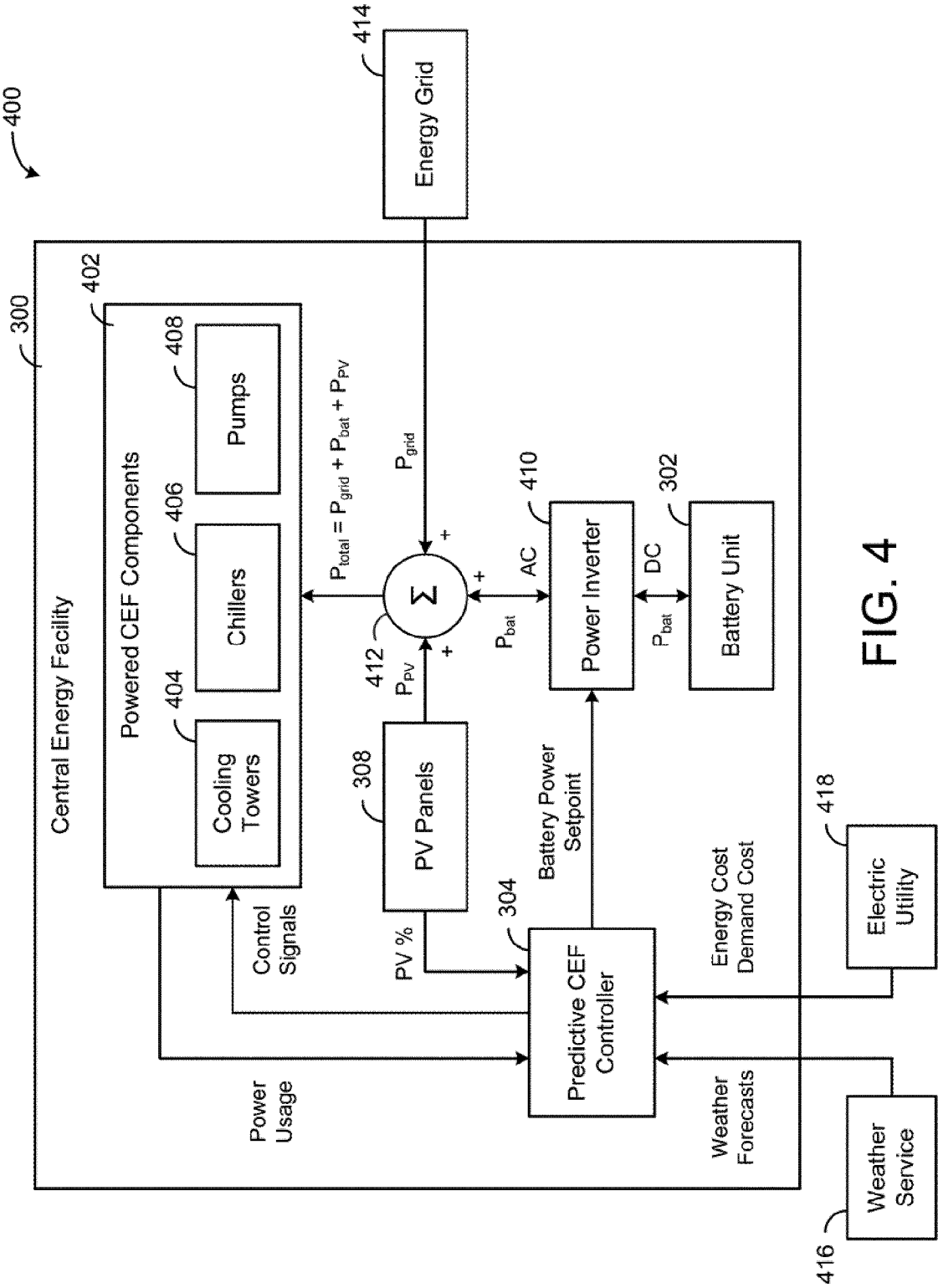


FIG. 4

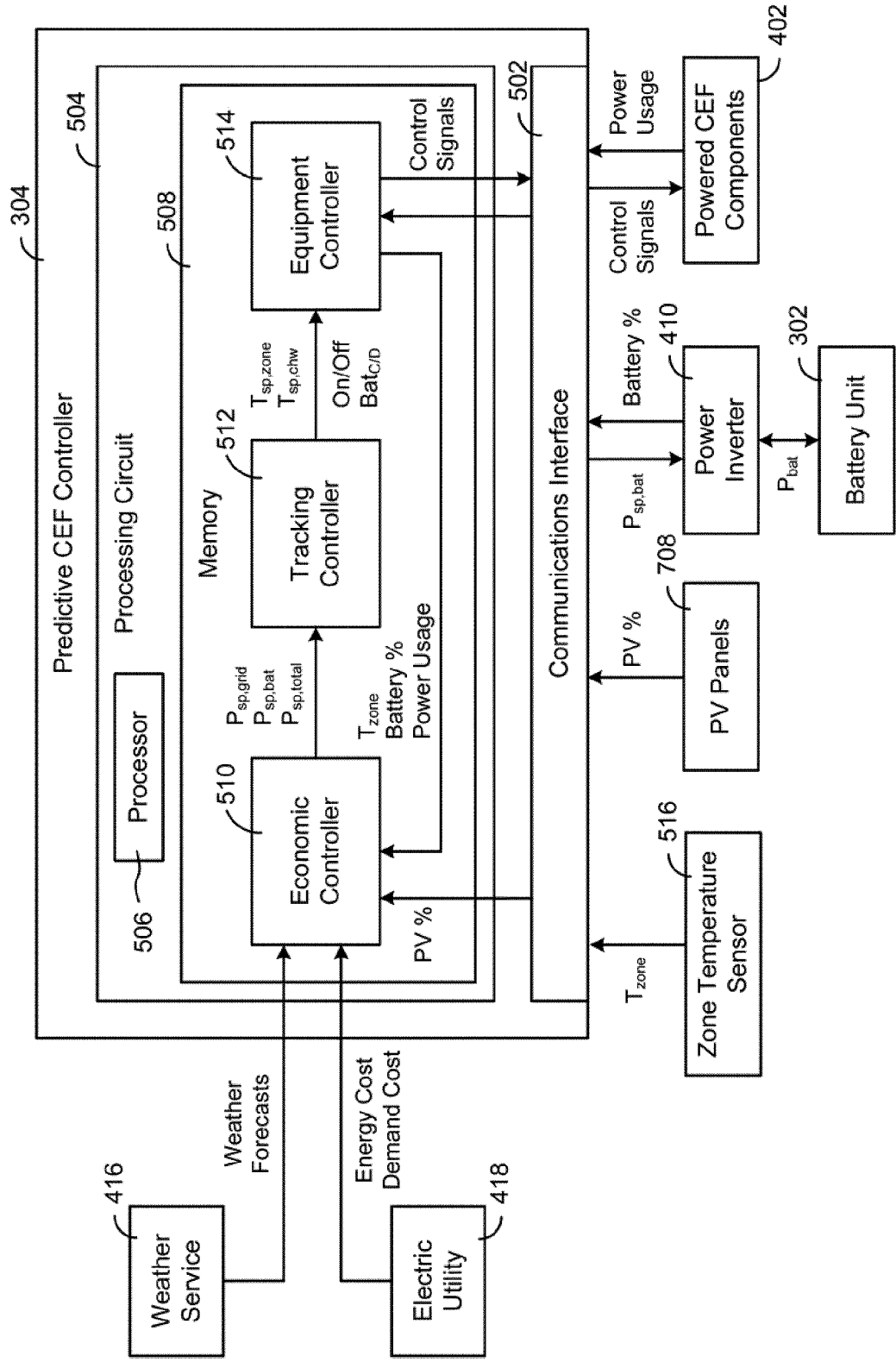


FIG. 5

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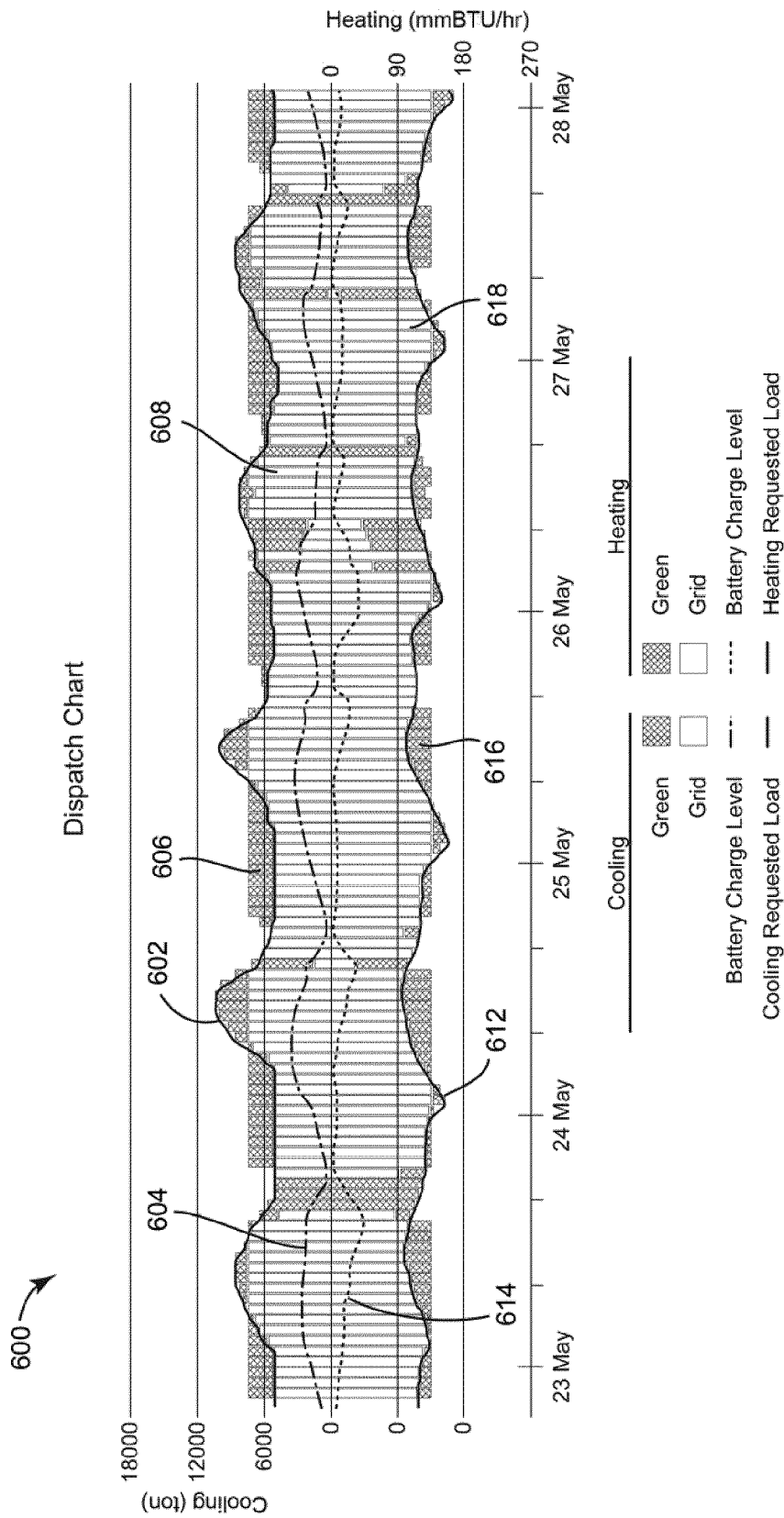


FIG. 6

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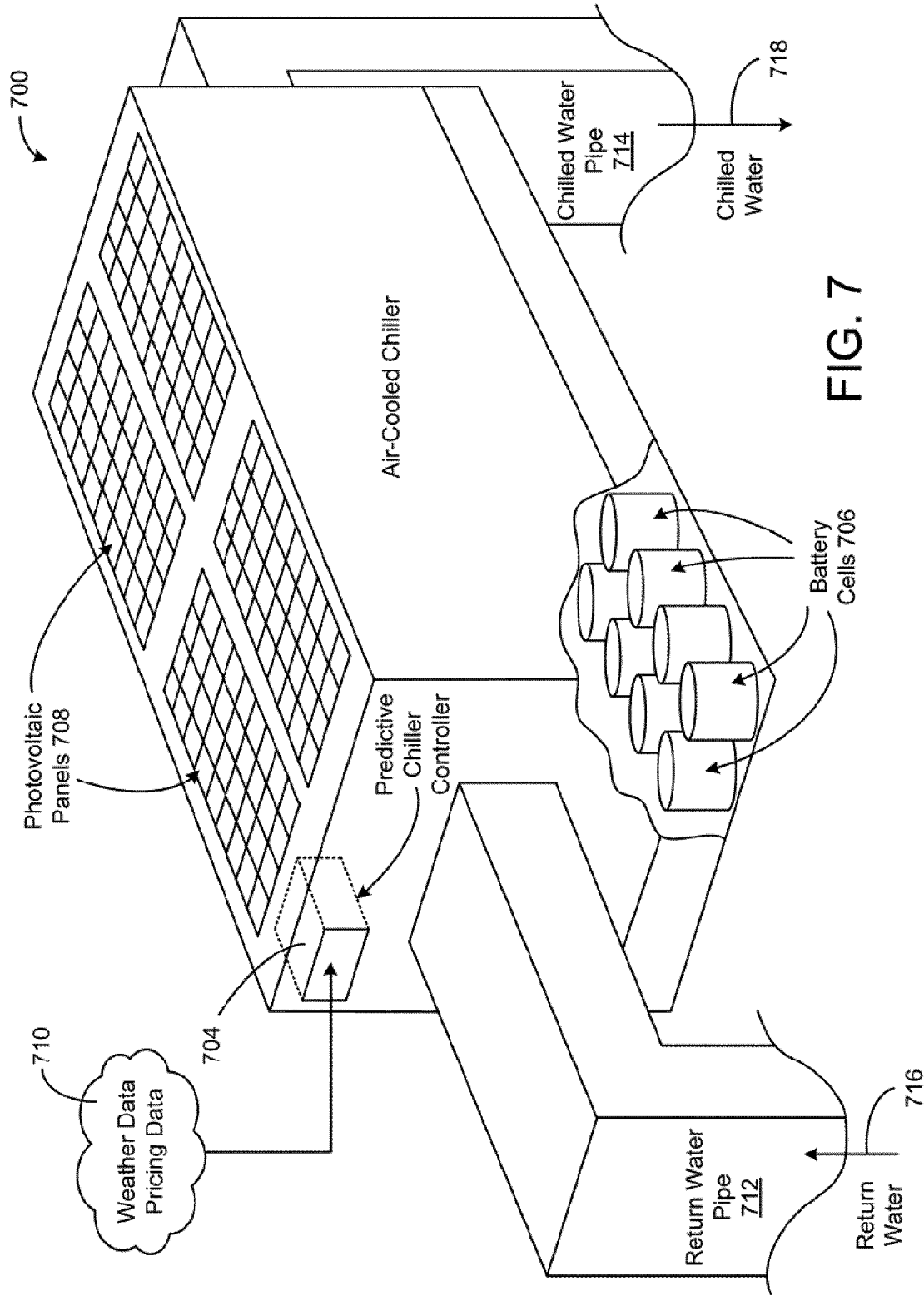
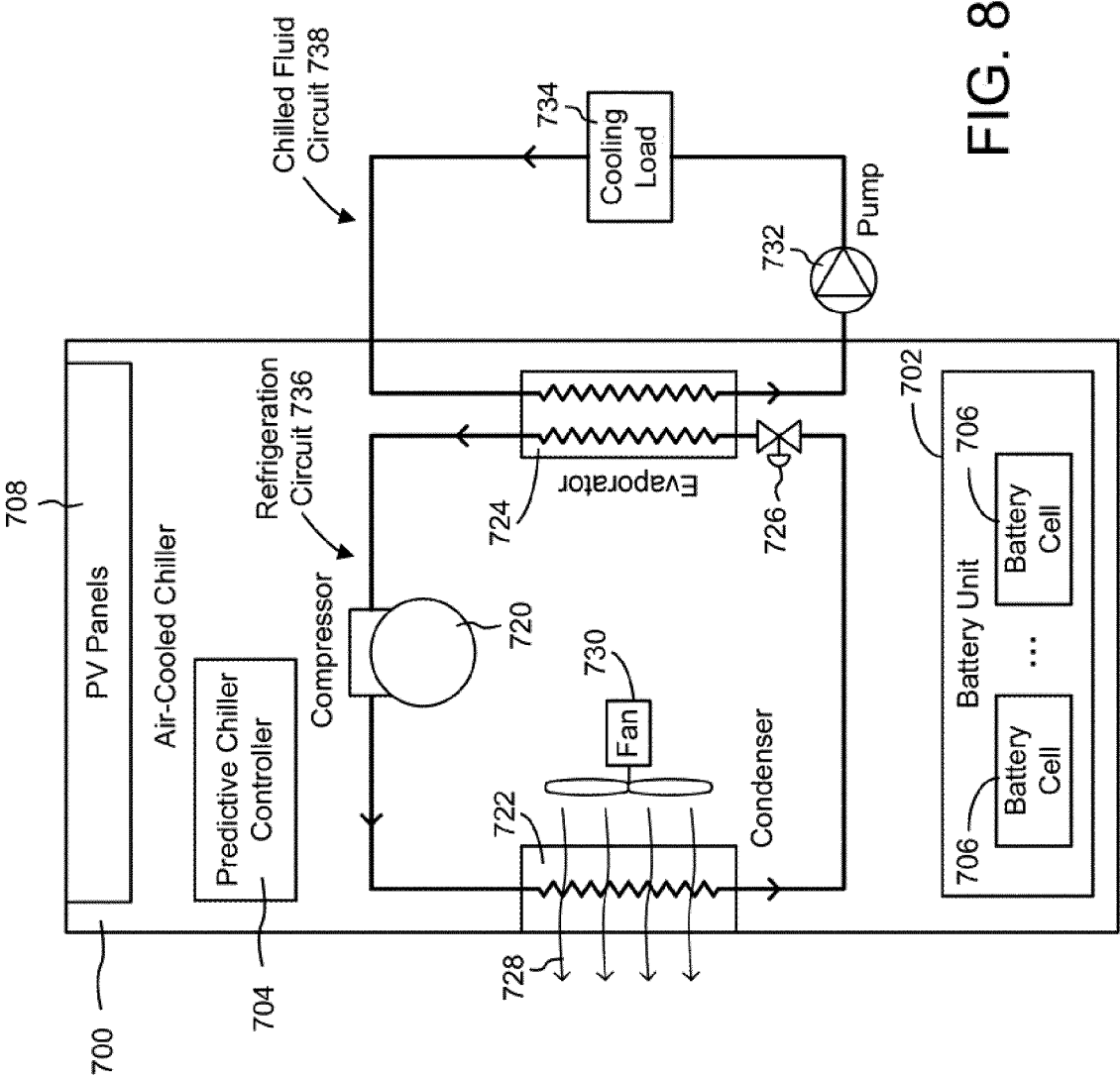


FIG. 7



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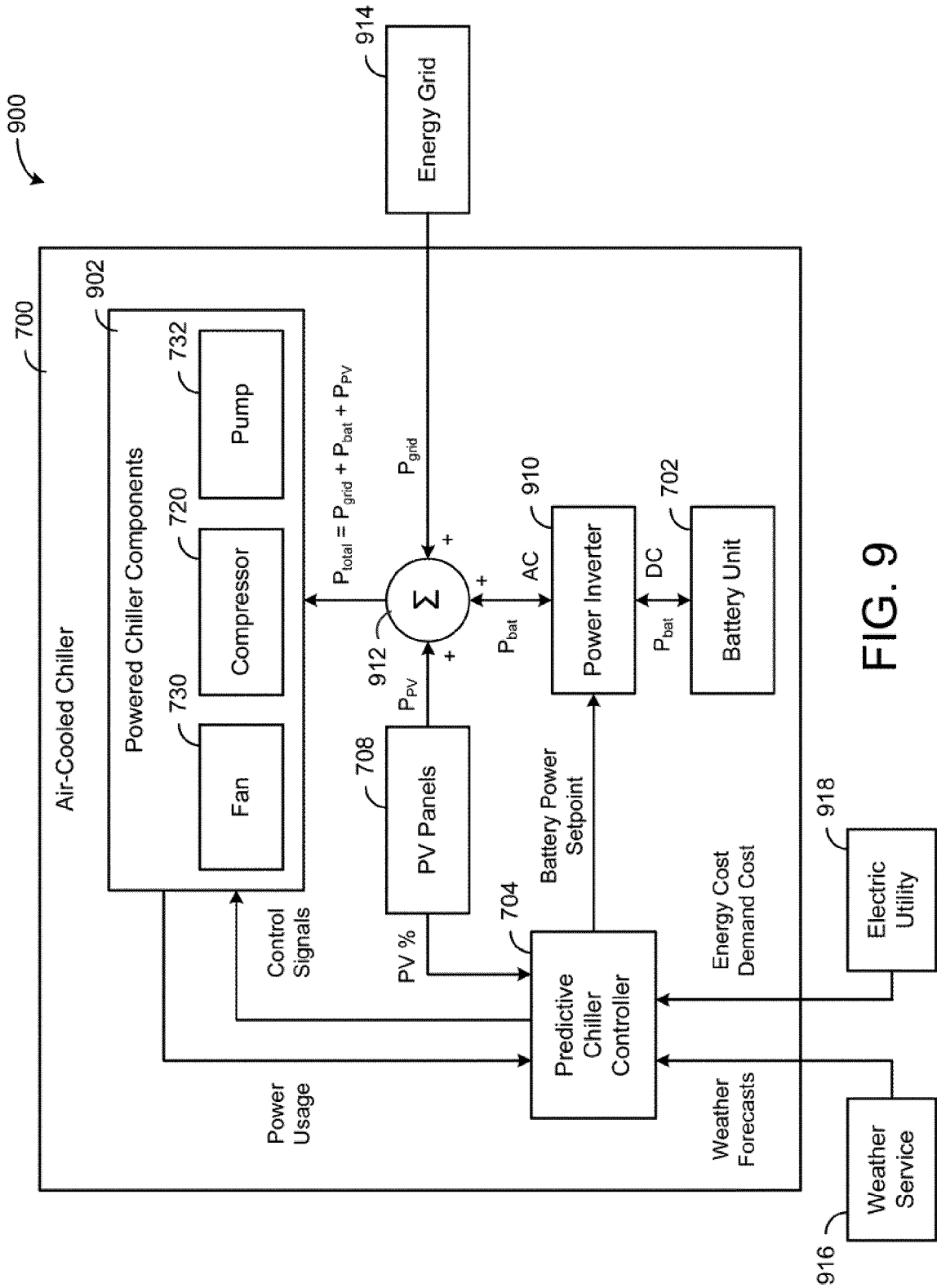


FIG. 9

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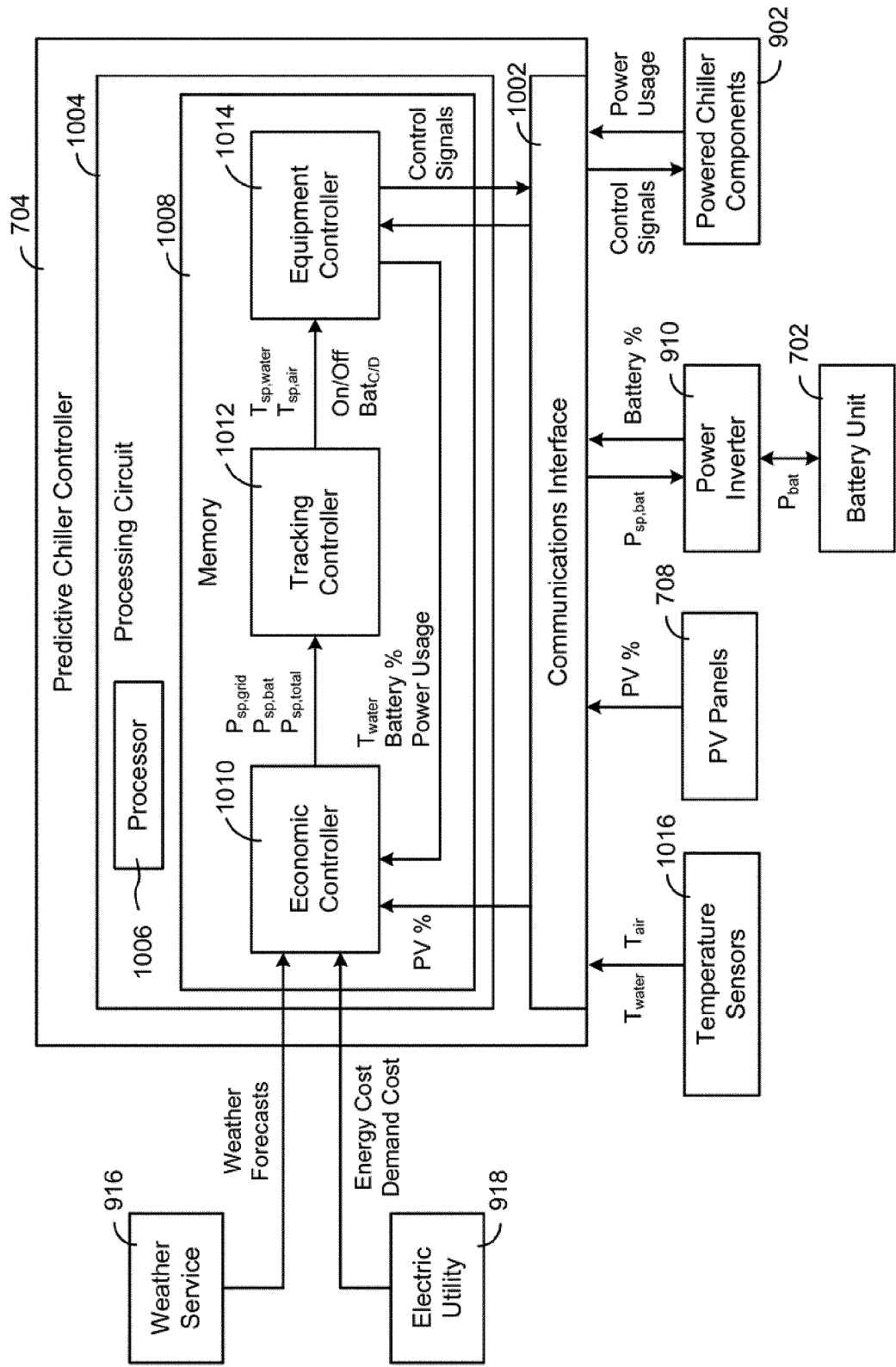


FIG. 10

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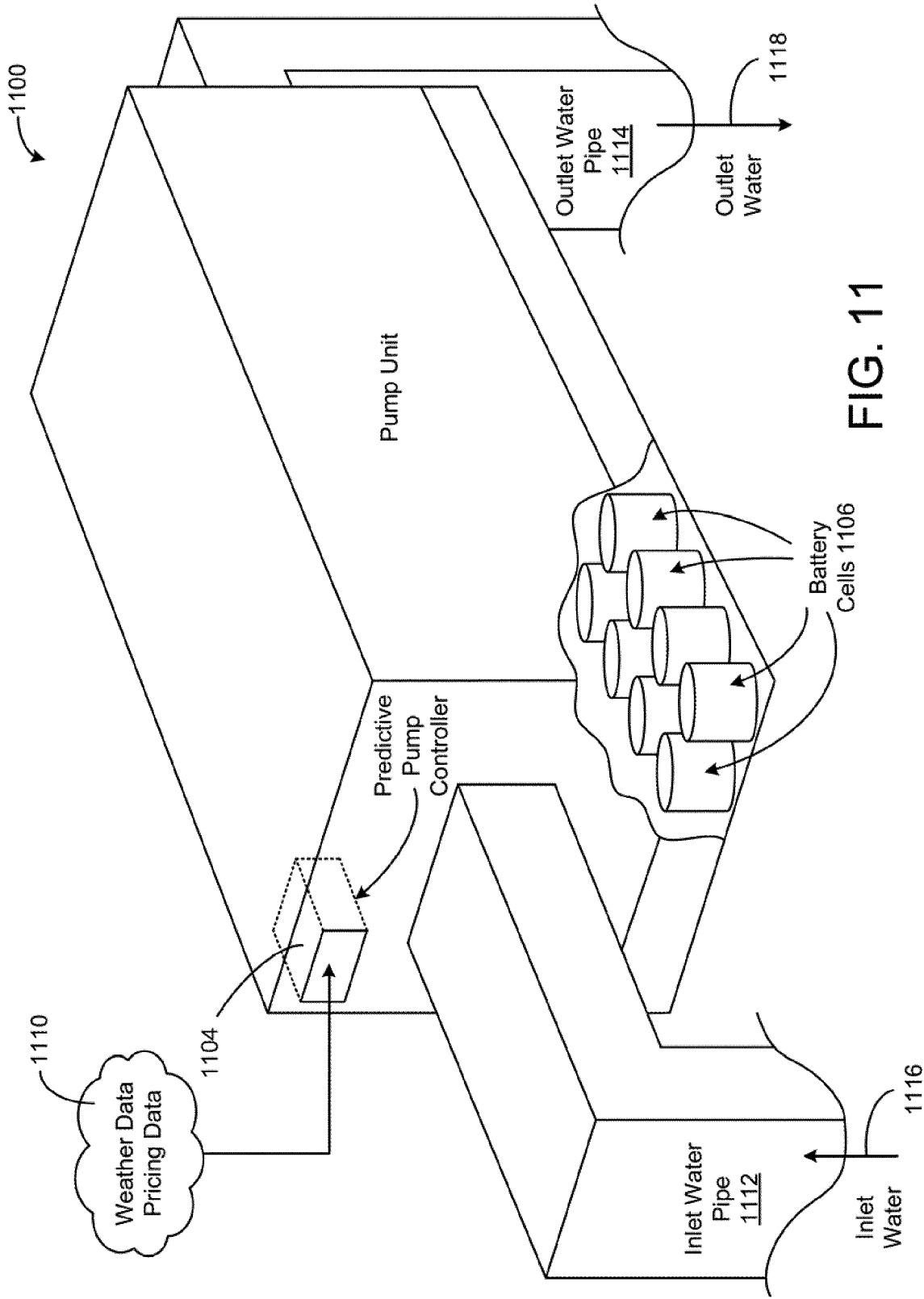


FIG. 11

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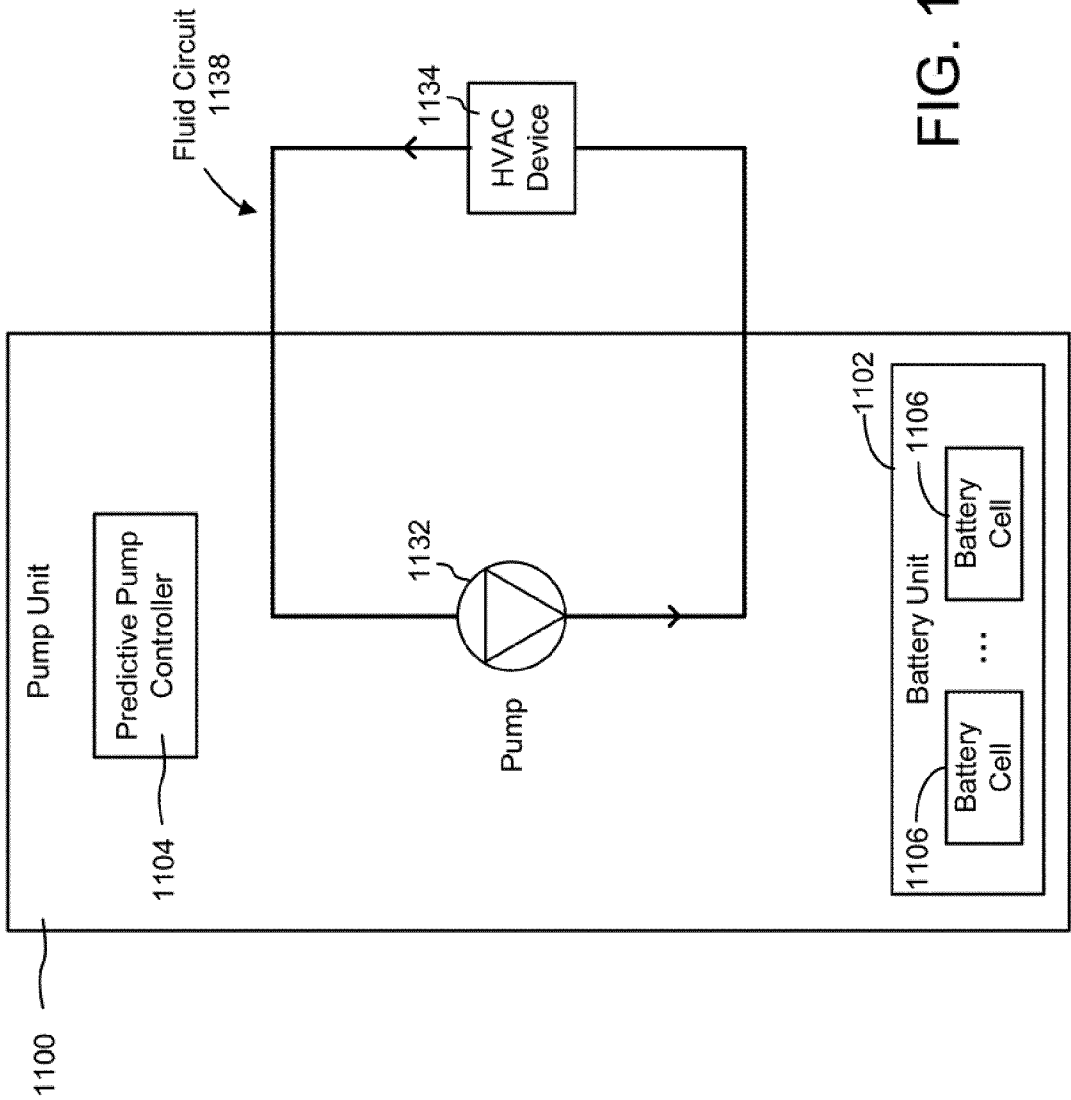


FIG. 12

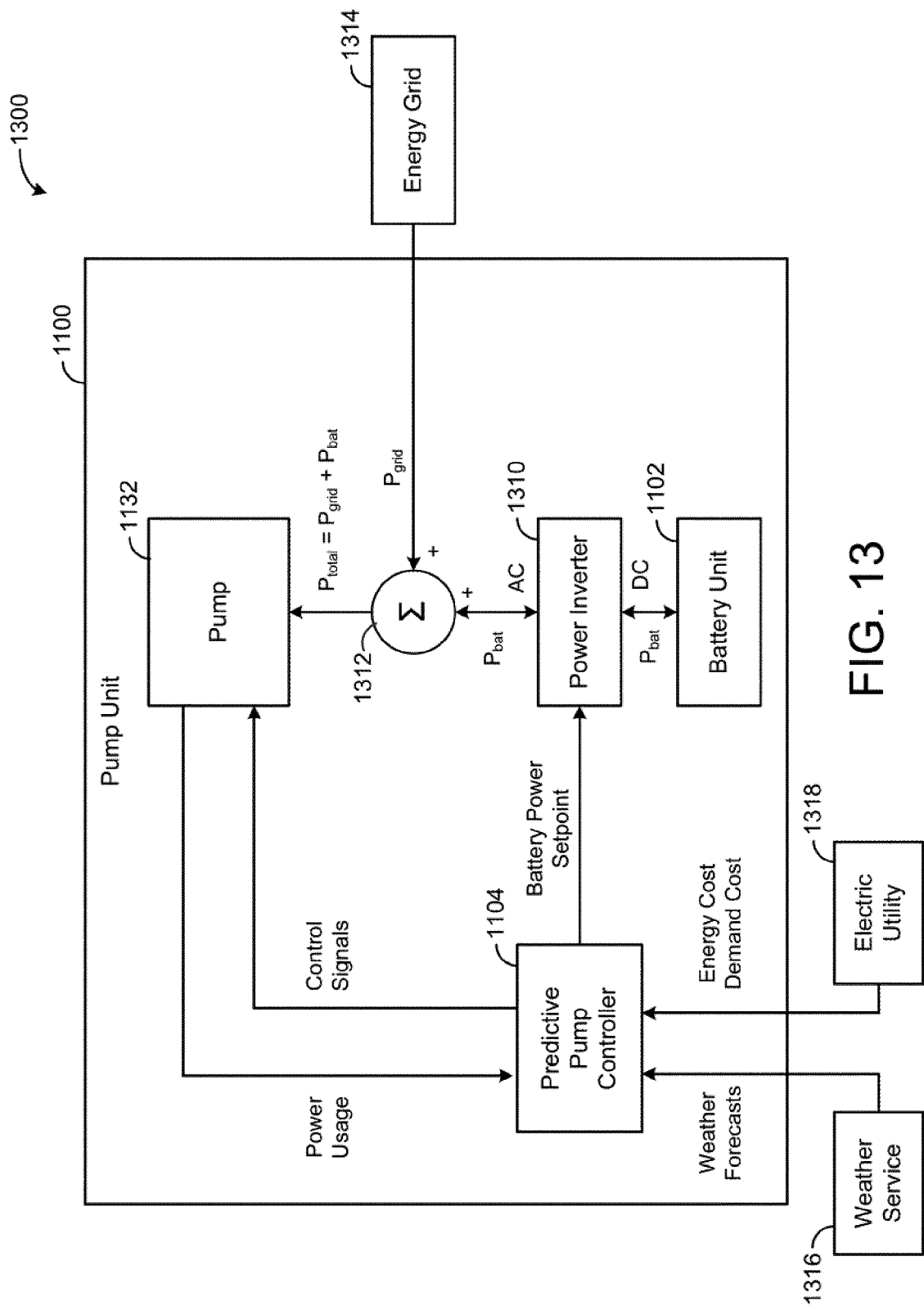


FIG. 13

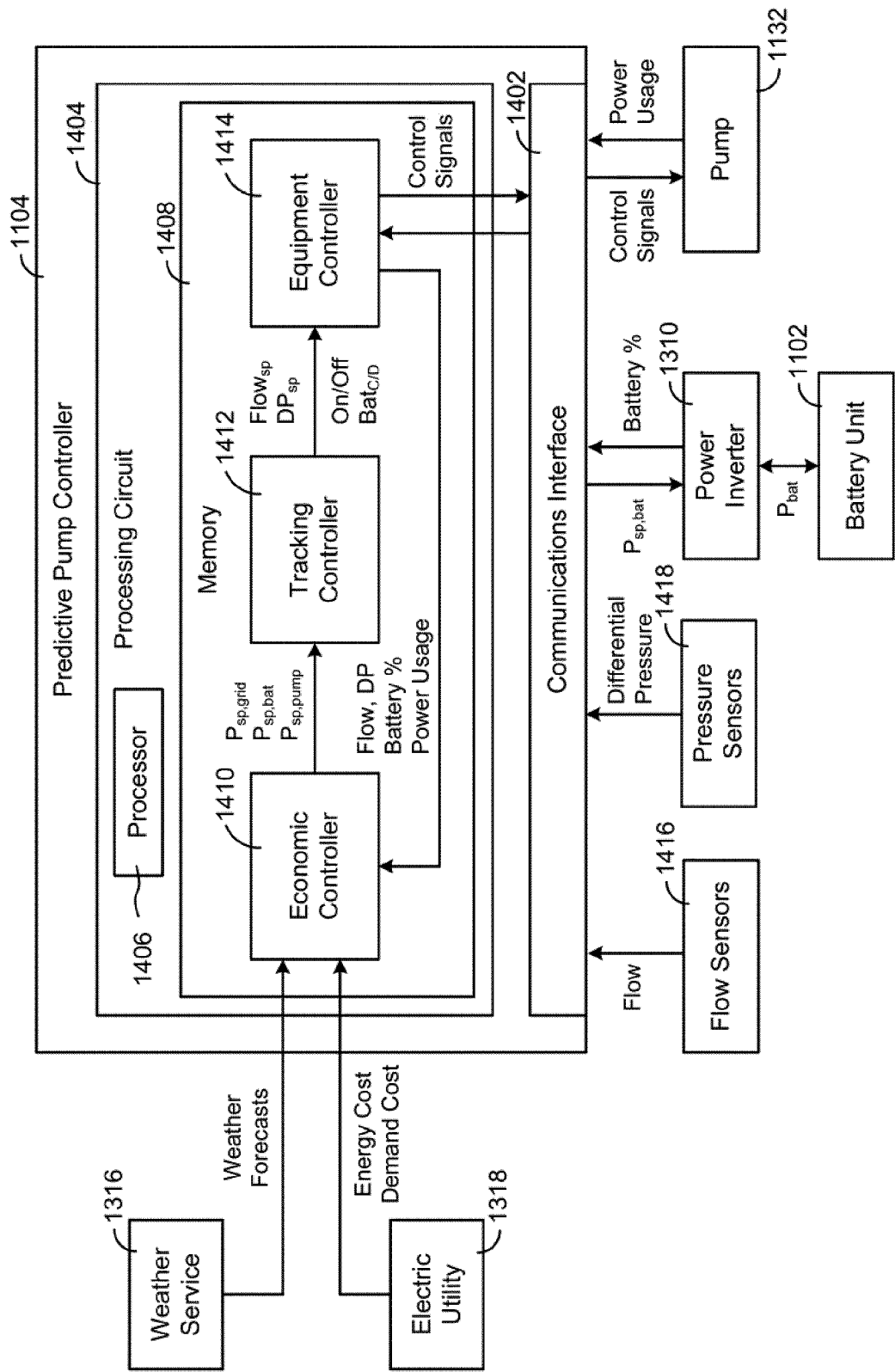


FIG. 14

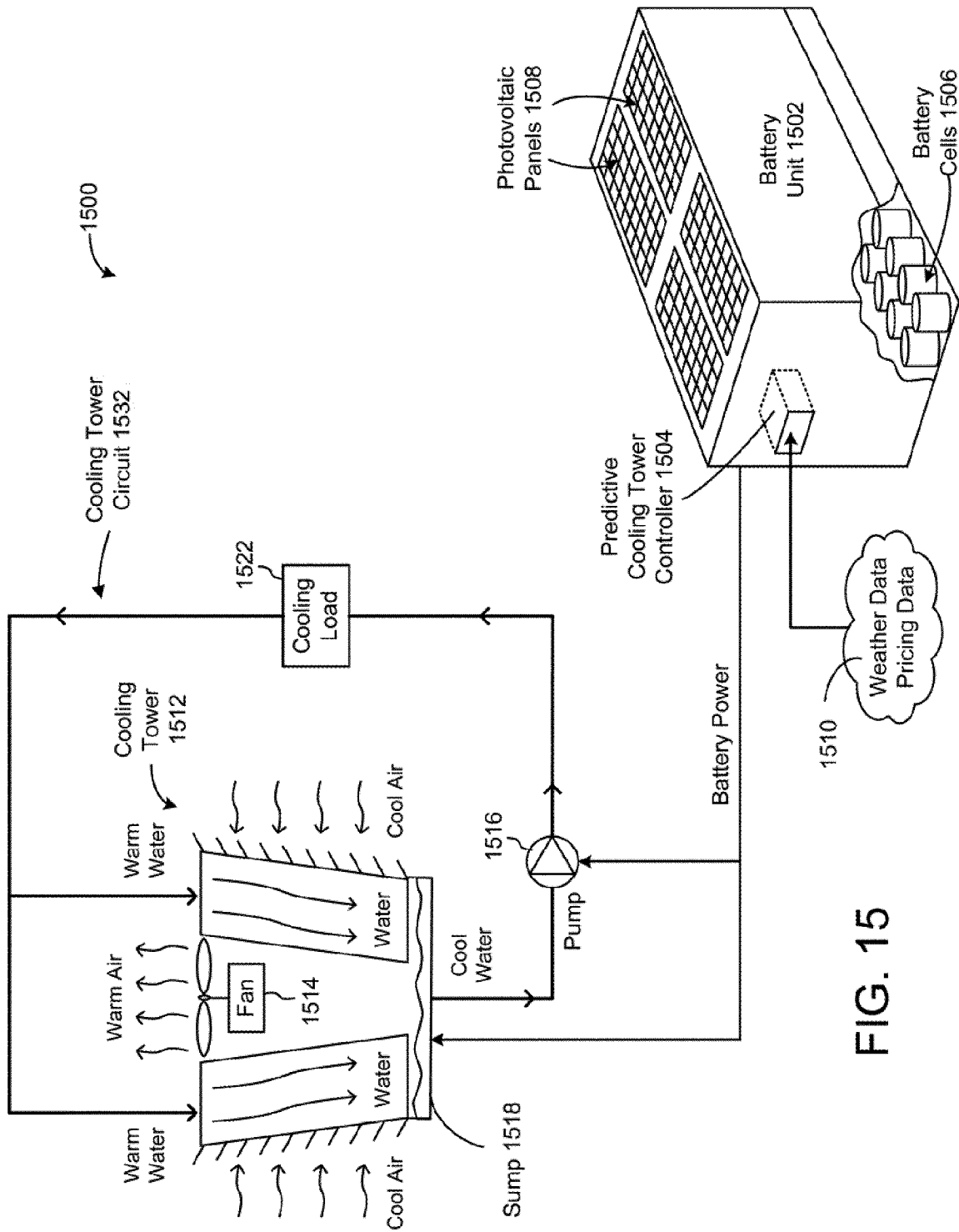


FIG. 15

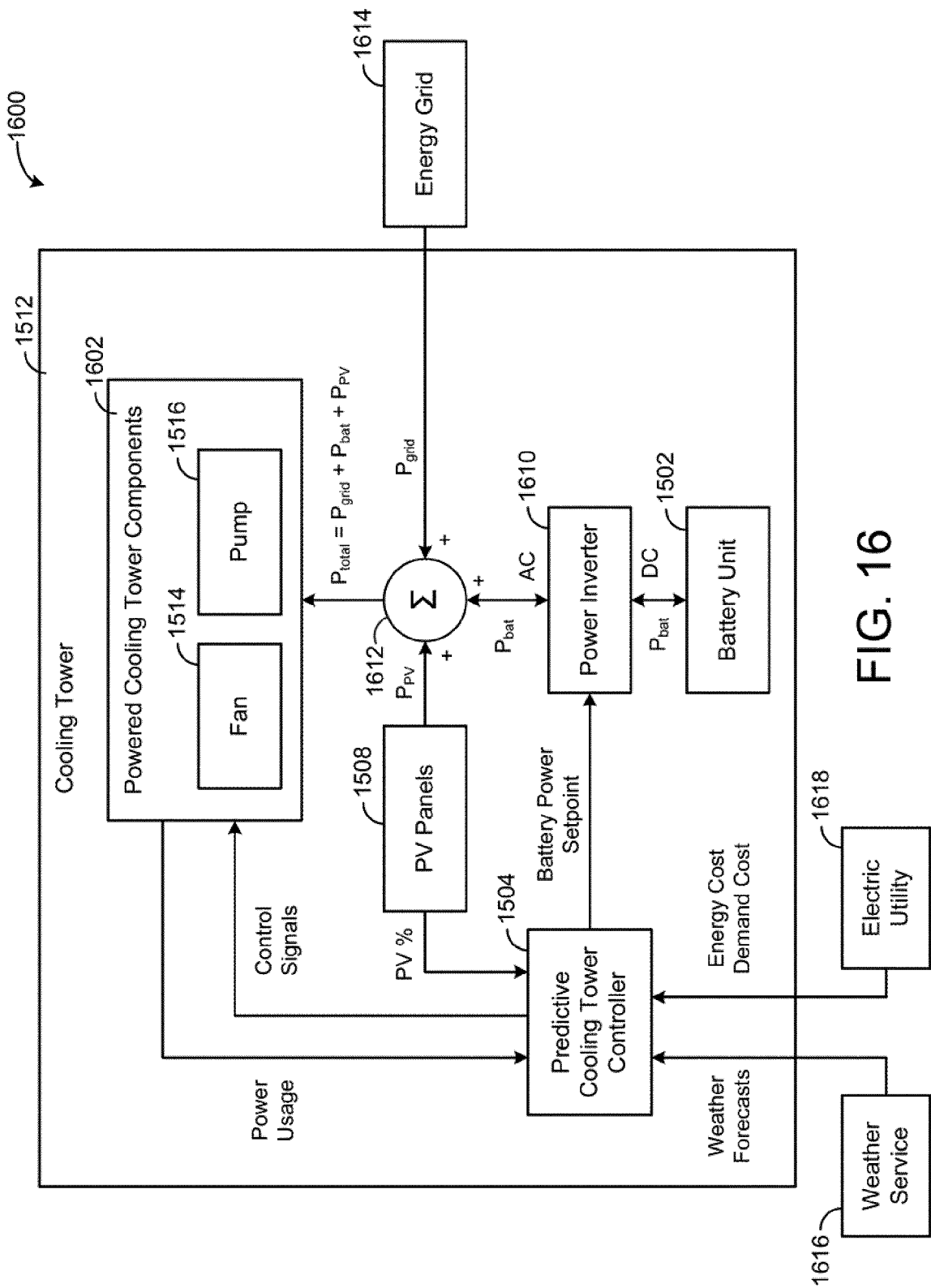


FIG. 16

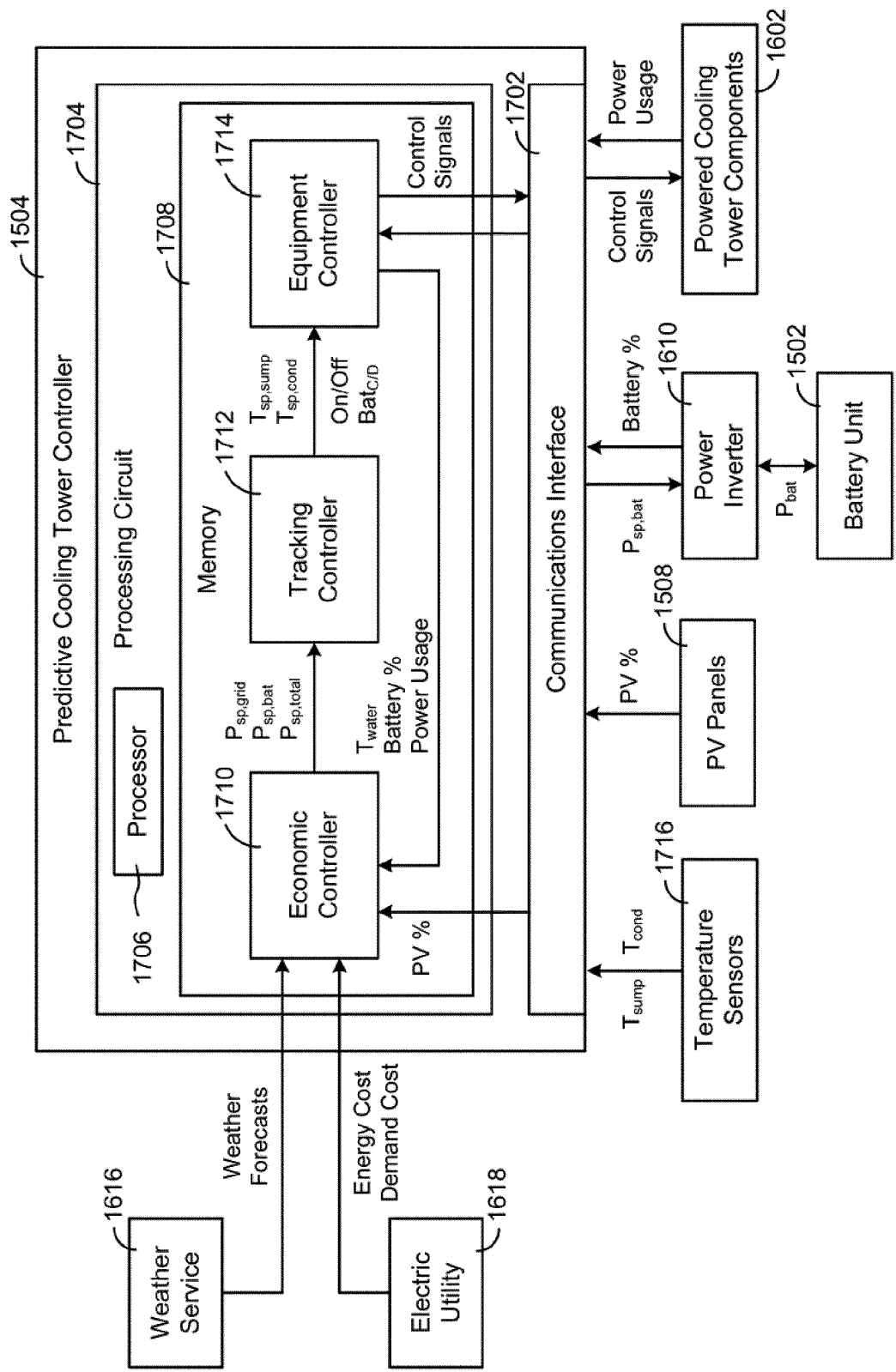


FIG. 17

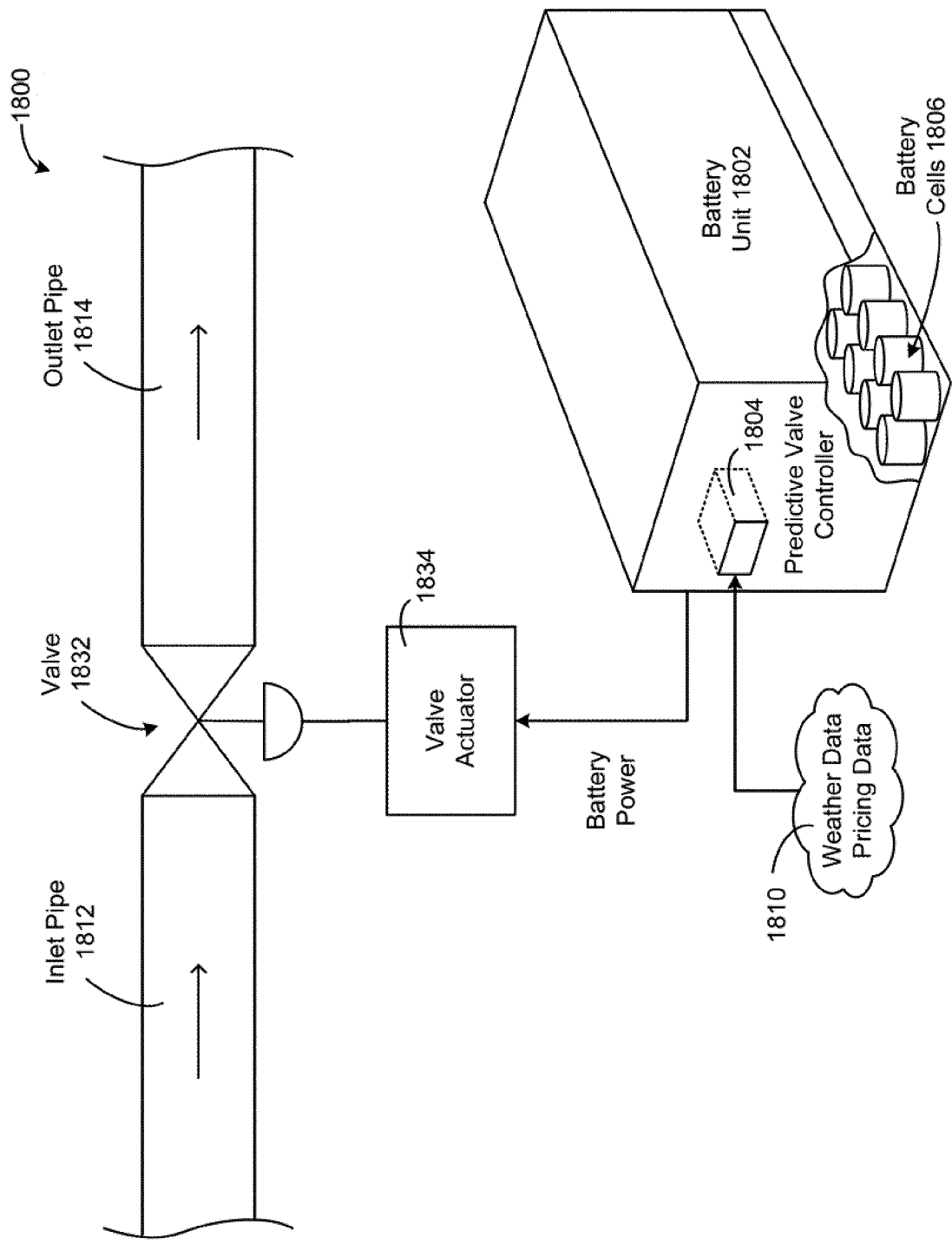


FIG. 18

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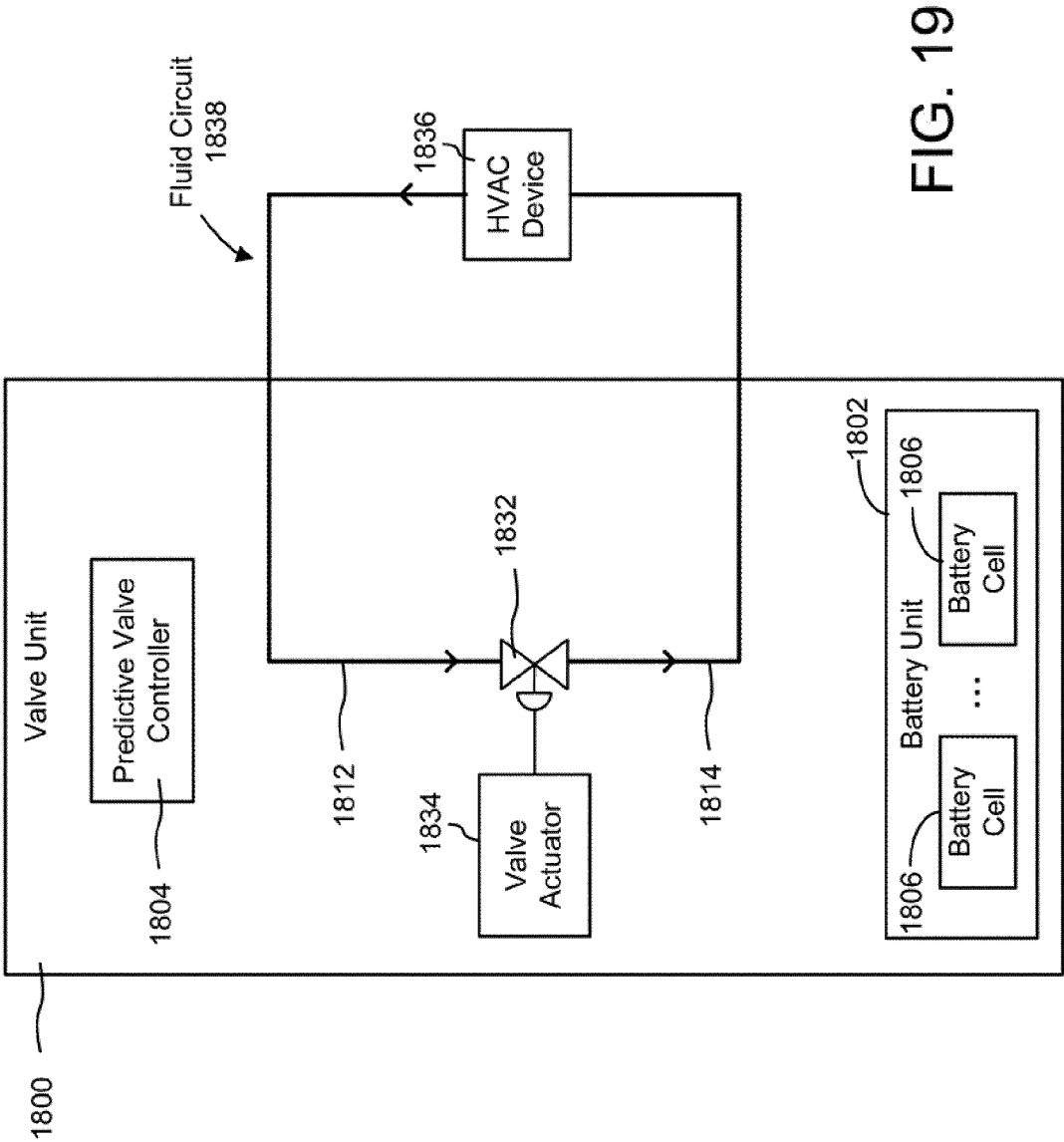
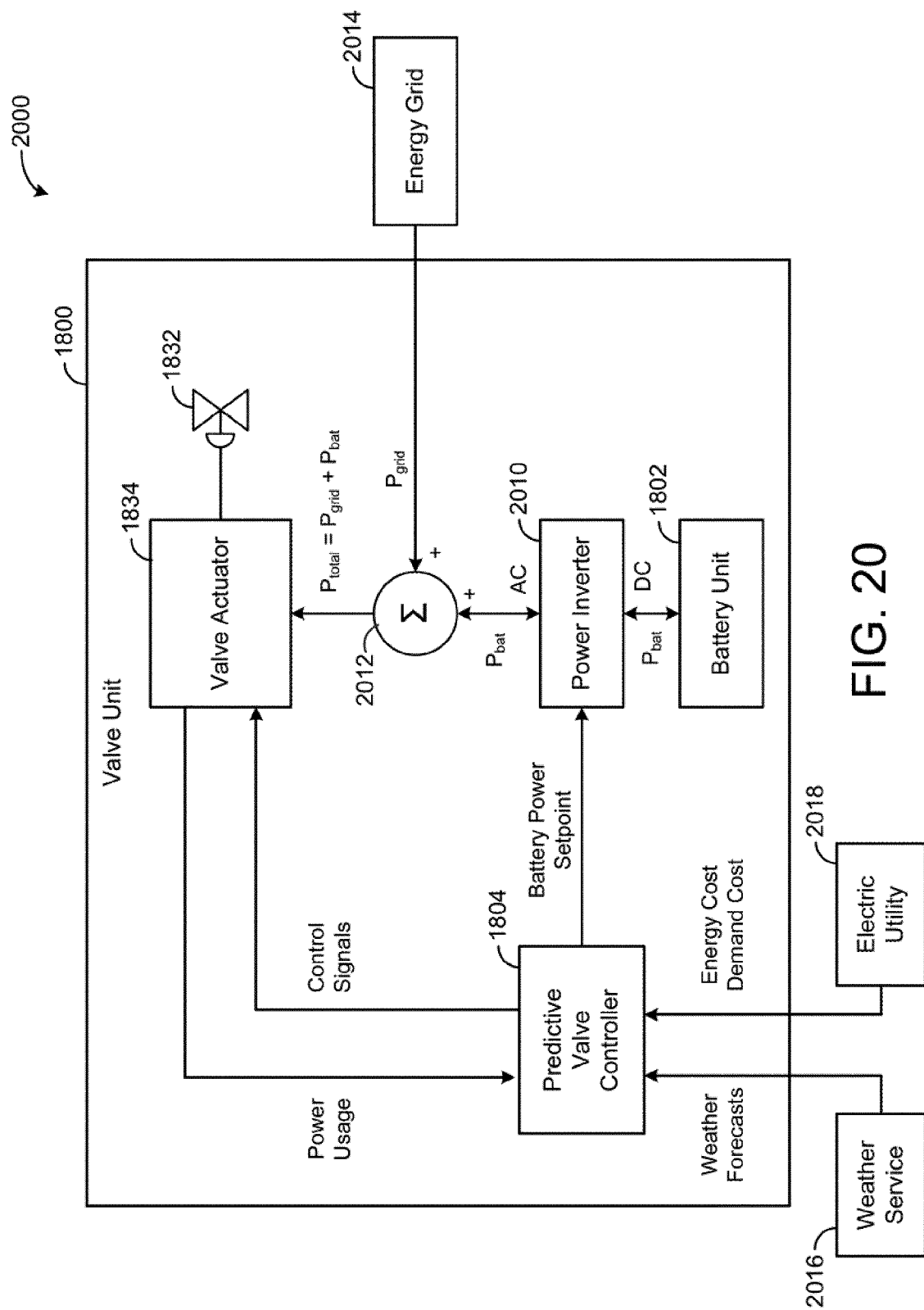


FIG. 19



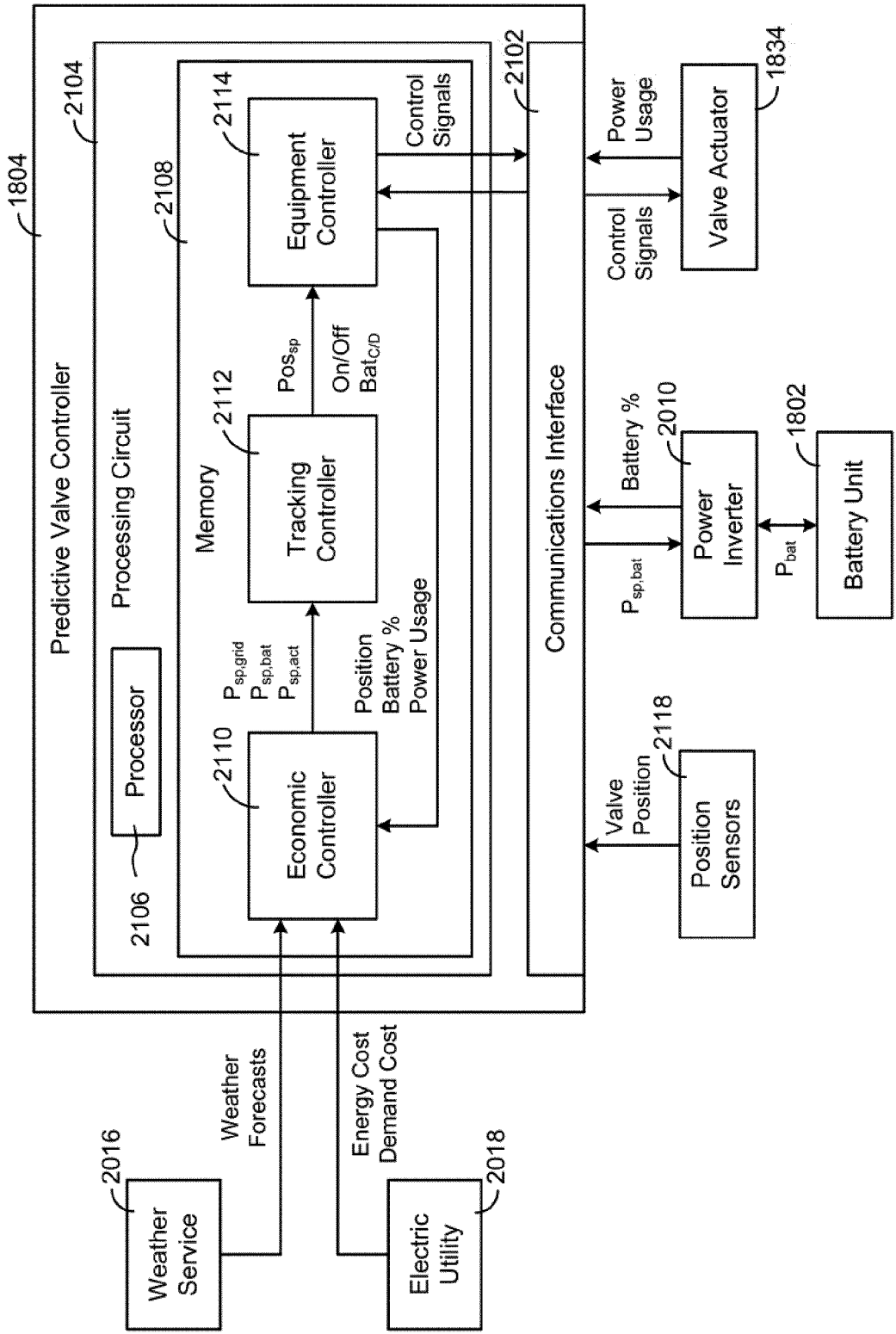


FIG. 21

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/039119

A. CLASSIFICATION OF SUBJECT MATTER

INV. G05B13/04 H02J3/32 F24F11/62
ADD.

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)

G05B H02J F24F

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TANGUY HUBERT ET AL: "Modeling for Residential Electricity Optimization in Dynamic Pricing Environments", IEEE TRANSACTIONS ON SMART GRID, IEEE, USA, vol. 3, no. 4, 1 December 2012 (2012-12-01), pages 2224-2231, XP011486181, ISSN: 1949-3053, DOI: 10.1109/TSG.2012.2220385 abstract page 2225 - page 2228 ----- -/--	1-28



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"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)

"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

"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

"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

"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

"&" document member of the same patent family

Date of the actual completion of the international search

26 September 2018

Date of mailing of the international search report

05/10/2018

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Dörre, Thorsten

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2018/039119

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2013/186282 A2 (FRONIUS INT GMBH [AT]) 19 December 2013 (2013-12-19) abstract pages 1-3 pages 8,9,17 pages 19,20,23 pages 28,29	1-28
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