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(54) **SYSTEM AND METHOD FOR CONVERTING ELECTRIC ENERGY INTO THERMAL ENERGY AND FOR STORING THERMAL ENERGY**

(57) The present invention refers to a system (10) and a method of operating the system (10). The system (10) contains a heat pump cycle (16), a turbine cycle (17), a medium storage cycle (11) and a water storage cycle (37). By means of the heat pump cycle (16), heat of a working fluid can be transferred to a thermal medium (M) for storing thermal energy. By means of the turbine cycle (17), heat of the thermal medium (M) can be transferred to a working fluid (F). In so doing electric energy can be converted into thermal energy or transferred from thermal energy into electric energy by operating either the heat pump cycle (16) or the turbine cycle (17). The thermal coupling between the water storage cycle (37) and the heat pump cycle (16) is provided by means of a water-to-fluid heat exchanger (36) and the thermal coupling between the water storage cycle (37) and the turbine cycle (17) is provided by means of a fluid-to-water heat exchanger (49). The water storage cycle (37) additionally contains an air-cooled water cooling unit (50) that can be operated independent from the water-to-fluid heat exchanger (36).

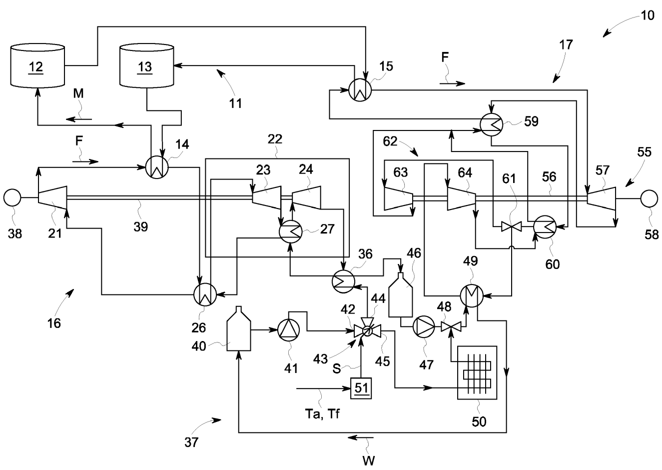

FIG. 1

EP 3 444 448 A1

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Description

[0001] The present invention refers to a system for converting electric energy into thermal energy and for storing the thermal energy. Such systems are for example used if power plants produce an excess of electric energy that is not needed for operating at least one electric load and/or for the power grid. Particularly power plants that produce electricity based on renewable energy concepts like wind turbine or photovoltaic power plants are subject to variations in the amount of electric power that is generated depending on the environmental conditions. Accordingly situations can occur, in which such power plants create an excess of electric power or are unable to produce sufficient electric power. In order to maintain operability of an electric load and/or maintain the grid stability it is beneficial to store excess electric energy produced by power plants and also to discharge the stored energy again, if needed.

[0002] Systems that are able to transform electric energy into thermal energy in order to store excess electric energy and also to transform the stored thermal energy back into electric energy to supply electric power to the grid are known in the prior art, e.g. from US 4 089 744 A, EP 2 942 492 A1 or EP 2 602 443 A1.

[0003] US 2016/0222830 A1 discloses a system having a heat pump cycle in which a working fluid can be circulated. The heat pump cycle comprises a compressor unit, an expander unit and a medium heating unit that is adapted to heat a thermal medium that can be circulated in a medium storage cycle. The heat pump cycle also contains a water-to-fluid heat exchanger for transferring heat from water that can be circulated in a water storage cycle to the working fluid. Further a turbine cycle is provided in which a working fluid can be circulated. The turbine cycle comprises a turbine unit, a medium cooling unit and a fluid-to-water heat exchanger. The medium cooling unit is adapted to cool the thermal medium circulating in the medium storage cycle and the fluid-to-water heat exchanger is adapted to transfer heat from the working fluid of the turbine cycle to the water of the water storage cycle. If electric energy shall be stored in the form of thermal energy, an electric motor drives the compressor unit and the thermal medium is heated by means of the medium heating unit. If on the other hand the stored thermal energy shall be discharged in form of electrical energy, the turbine cycle is operated and the turbine unit creates electric energy. The working fluid in the turbine cycle is heated by means of the medium cooling unit so that the thermal energy is transferred into electric energy created by the turbine unit.

[0004] In such a system the efficiency of the turbine cycle and the heat pump cycle might be different. They are thermally coupled with each other by means of the water storage cycle. If a specific amount of thermal energy is drawn from the stored thermal medium by operating the turbine cycle and subsequently the same amount of thermal energy is replaced by operating the heat pump cycle, an imbalance condition with regard to the amount of hot and cold water in the water storage cycle can occur, which can affect the availability of the system.

[0005] An object of the present invention is to improve such a conventional system in order to improve the overall efficiency.

[0006] The object of the present invention is solved by means of a system for converting electric energy into thermal energy and for storing thermal energy which may comprise a heat pump cycle in which a working fluid may be circulated. The heat pump may comprise a first compressor unit for compressing the working fluid, and/or an expander unit for expanding the working fluid, and/or a medium heating unit which may be fluidly connected so that the medium heating unit may be fluidly connected downstream of the first compressor unit and upstream of the expander unit. Preferably, a water-to-fluid heat exchanger may be fluidly connected to the heat pump cycle downstream of the expander unit. The medium heating unit may be adapted to heat a thermal medium that may be circulated in a medium storage cycle, wherein the water-to-fluid heat exchanger may be adapted to transfer heat from water that can be circulated in a water storage cycle to the working fluid.

[0007] The system may further comprise a turbine cycle in which a working fluid may be circulated. The turbine cycle may comprise a turbine unit, and/or a medium cooling unit and/or a fluid-to-water heat exchanger that may be fluidly connected so that the medium cooling unit may be upstream of the turbine unit. Preferably, the fluid-to-water heat exchanger may be downstream of the turbine unit, wherein the medium cooling unit may be adapted to cool the thermal medium of the medium storage cycle. The fluid-to-water heat exchanger may be adapted to transfer heat from the working fluid to the water of the water storage cycle.

[0008] The water storage cycle may comprise a hot water tank, and/or a controllable valve unit downstream of the hot water tank which may have a first outlet port and preferably a second outlet port. The first outlet port may be fluidly connected via the water-to-fluid heat exchanger with a cold water tank and/or with the fluid-to-water heat exchanger. The second outlet port may be fluidly connected via a water cooling unit with the cold water tank and/or with the fluid-to-water heat exchanger.

[0009] According to another aspect of the invention, there is provided a method of operating a system for converting electric energy into thermal energy and for storing thermal energy. The method may comprise one or more of the following steps:

- if electrical energy shall be stored in form of thermal energy: driving the first compressor unit in order to transfer heat from the working fluid of the heat pump cycle to the thermal medium of the medium storage cycle;

- if electrical energy shall be produced by the turbine unit: transferring heat from the thermal medium of the medium storage cycle to the working fluid of the turbine cycle, supplying working fluid to operate the turbine unit thereby transferring heat from the working fluid of the turbine cycle to the water of the water storage cycle by means of the fluid-to-water heat exchanger, preferably the amount of water supplied to the water-to-fluid heat exchanger and/or the amount of water supplied to the water cooling unit may be controlled by means of the controllable valve unit.

[0010] The system of the present invention comprises a medium storage cycle containing the thermal medium. The turbine cycle may have a medium cooling unit and the turbine unit may be thermally coupled with the water storage cycle by means of the fluid-to-water heat exchanger. The heat pump cycle may be thermally coupled with the water storage cycle by means of a water-to-fiuid heat exchanger. The water cooling unit may be an air-cooled water cooling unit, which may be adapted to cool water of the water storage cycle that may be drawn from the hot water tank. The controllable valve unit may be provided downstream of the hot water tank having the first outlet port and preferably the second outlet port. The first outlet port may be fluidly connected with the first outlet line and the second outlet port may be fluidly connected with the second outlet line. The outlet lines may be connected with a cold water tank and/or the water heater respectively. The water can thus either be cooled by means of the water-to-fluid heat exchanger coupling the water storage cycle with the heat pump cycle or by means of the water cooling unit. The amount that is cooled by the water-to-fluid heat exchanger or the water cooling unit is controlled by means of the controllable valve unit.

[0011] Drawing heat of a given amount from the thermal medium of the medium storage cycle produces a greater volume of warm water compared with the volume of cold water that is created when replacing the thermal energy of the thermal medium by using the heat pump cycle. Accordingly in the conventional system the cold tank of the water storage cycle will not fill up at the same rate as the hot water tank and on average the cold water tank is unable to fulfil the requirement of cooling the working fluid of the turbine cycle. By additionally providing a water-cooling unit, that preferably cools the water by ambient air, the cooling requirement of the turbine cycle can be fulfilled. Running out of cold water is avoided and the system provides an increased availability and efficiency.

[0012] It is preferred that the water storage cycle may be a closed loop and no additional fresh cold water needs to be supplied in order to fulfil the cooling requirement and to keep the system available. The cooling performance of the water cooling unit is sufficient. In one preferred embodiment the water cooling unit is air-cooled and is able to cool the water to a water temperature in a range near the temperature of the ambient air, e.g. in a range between the ambient air temperature and the ambient air temperature +10°C.

[0013] It is preferred that flow rate of water flowing through the water cooling unit and/or through the water-to-fluid heat exchanger may be adjusted by means of the valve unit. The setting of the valve unit may depend on the operating requirements of the system. For example a control unit may be used to control the valve unit. The control unit may create a control signal depending on parameters like operating parameters of the system and/or environmental parameters like the actual ambient air temperature and/or a forecast ambient air temperature. Particularly using the forecast ambient air temperature may increase the flexibility and efficiency of the system. A forecast air temperature increase may be considered and the system operating condition may be varied to prepare for the temperature increase and the reduced cooling ability of the air-cooled water cooling unit. If, for example, a warm day is forecast, the volume of cold water stored in the cold water tank may be increased by operation of the air-cooled water cooling unit at a higher load. If due to the warm day the air-cooled water cooling unit cannot be used or with lower cooling performance, the system may be prepared and the cold water tank may provide sufficiently cold water for cooling the working fluid of the turbine cycle and thus for keeping the system available. As a consequence maintaining the grid stability by charging and discharging electric energy to the grid or from the grid respectively is improved.

[0014] In a preferred embodiment of the system the medium storage cycle may be a closed loop and may comprise a hot medium reservoir downstream of the medium heating unit and/or a cold medium reservoir downstream of the medium cooling unit. The thermal medium used in the medium storage cycle is preferably a fluid and particularly a molten salt.

[0015] The turbine cycle may contain a second compressor unit adapted to compress the working fluid of the turbine cycle. The second compressor unit may be driven by means of a turbine rotor or turbine shaft of the turbine unit. The second compressor unit may contain one or more compressor stages.

[0016] It is also advantageous to provide a first heat exchanger in the heat pump cycle. A heat discharge section of the first heat exchanger may be fluidly connected downstream of the medium heating unit and/or upstream of the expander unit. The heat charging section of first heat exchanger may be fluidly connected downstream of the expander unit and upstream of the first compressor unit. The first heat exchanger may be a recuperator.

[0017] In a preferred embodiment the expander unit comprises at least two expander devices, preferably a first expander device and a second expander device. The first and second expander devices are preferably fluidly connected in parallel with each other. The expander devices may be staged such that the first expander device may be subject to higher working fluid temperatures than the second expander device. In such an embodiment it may be advantageous when the second expander device is fluidly connected downstream of a heat discharge section of a second heat exchanger that is preferably fluidly connected downstream of the first expander device. The heat charging section of the second heat exchanger may be fluidly connected downstream of the first expander device. The second heat exchanger can be a recuperator.

[0018] It is advantageous that downstream of the first heat exchanger a first fluid valve may be provided for splitting the working fluid in two split streams, wherein one of the split streams is conducted to the first expander device and the other of the split streams is conducted to the second expander device. A second fluid valve may be provided downstream of the first expander device and the second expander device, that mixes the working fluid streams delivered from the two expander devices. The first fluid valve is preferably adjusted or controlled to adjust the mass flow of the split streams of the working fluid delivered to the expander devices. In so doing a desired temperature and/or a desired pressure of the fluid streams delivered from the two expander devices can be achieved. For example, the fluid streams delivered from the two expander devices can have the same pressure and/or temperature within predefined tolerances.

[0019] It is also possible to provide more than two expander devices of the expander unit. Such multiple expanders can account for varying properties of the working fluid in order to increase the efficiency. Also the at least one expander device that operates at working fluid temperatures below a temperature limit of e.g. 100°C or 80°C or less can have a conventional design which is cost effective.

[0020] The working fluid that can be used in the heat pump cycle and/or the turbine cycle can be a gas, preferably carbon dioxide (CO_2).

[0021] Preferred embodiments of the invention are contained in the dependent claims, the description and the drawings.

[0022] In a further preferred embodiment in which a control unit may be present which may be adapted to control the controllable valve unit depending on at least one environmental parameter. The at least one environmental parameter may comprise the actual air temperature and/or a forecast air temperature in the vicinity of the water cooling unit.

[0023] Preferably, the working fluid of the heat pump cycle and/or the turbine cycle is a gas, and/or wherein the thermal medium of the medium storage cycle is a molten salt.

[0024] The heat pump cycle and the turbine cycle may be either fluidly separated closed loops or either a common integrated fluid circuit.

[0025] In the following, preferred embodiments are described in detail referring to the attached drawings, in which:

figure 1 is a schematic block diagram of a preferred embodiment of a system according to the present invention,

figure 2 is a schematic block diagram of a preferred embodiment of the heat pump cycle shown in figure 1,

figures 3-6 each show a schematic block diagram illustrating the function of the invention by way of exemplary operating and/or environmental conditions, and

figures 7 and 8 a schematic block diagram illustrating another embodiment of the system having a compact design with less heat exchanging units.

[0026] Figure 1 shows an embodiment of a system 10. The system 10 is adapted to convert electric energy into thermal energy and to store the thermal energy by using a thermal medium M that can be circulated in a medium storage cycle 11. Also the system 10 is adapted to convert stored thermal energy back into electric energy. In so doing the system 10 can be used to draw excess electric power from a power grid or power plant and to provide electric power to the power grid or an electric load as required. Thus the system 10 is particularly able to maintain the stability of a power grid. The system 10 is particularly advantageous in connection with power plants that create electric power from renewable energy, like solar power or wind power, that highly depends on environmental conditions. In such power plants the produced electric power is only controllable within certain limits and it is undesired to reduce electricity production or disconnect a power plant from the load or grid if less electric power is required, due to negative impacts on the efficiency of the power plant.

[0027] The medium storage cycle 11 comprises a hot medium reservoir 12 for storing hot thermal medium M and a cold medium reservoir 13 for storing cold thermal medium. The terms "hot" and "cold" in this description refer to a temperature difference of a respective medium or fluid, wherein "hot" means a location at which a medium or fluid has a higher temperature compared with a "cold" location within the same cycle. Accordingly the temperature of a fluid or medium in a hot tank or reservoir is higher than in a cold reservoir or tank. The absolute value of the temperatures depends on specific system designs and varies depending on the used components of the system, the used fluids, media and the like.

[0028] The medium storage cycle 11 is a closed loop in the preferred embodiment. The thermal medium M is in the present example a fluid and preferably a molten salt. Other media can also be used. The medium storage cycle 11 contains a medium heating unit 14 that is fluidly connected downstream of the cold medium reservoir 13 and upstream of the hot medium reservoir 12. A thermal medium M flowing from the cold medium reservoir 13 is heated by means of the medium heating unit 14 and subsequently supplied to the hot medium reservoir 12. Fluidly downstream from the hot medium reservoir 12 and fluidly upstream from the cold medium reservoir 13 a medium cooling unit 15 is provided. The medium heating unit 14 and the medium cooling unit 15 are in the present example heat exchangers and preferably recuperators. The medium heating unit 14 is adapted to transfer heat of a working fluid F that can be circulated in a heat pump cycle 16 to the thermal medium M. The medium cooling unit 15 is adapted to transfer heat from the thermal medium M to a working fluid F that can be circulated in a turbine cycle 17. The heat pump cycle 16 and the turbine cycle 17 are not fluidly connected with each other. Both cycles 16, 17 are thermally coupled by means of the medium heating unit 14 and the medium cooling unit 15 with the medium storage cycle 11 respectively.

[0029] As working fluid F for the heat pump cycle 16 and/or the turbine cycle 17 a gas and/or liquid and/or vapor can be used. In the present example a gaseous working fluid F is provided, preferably carbon dioxide (CO_2).

[0030] The heat pump cycle 16 is in the example according to figures 1 and 2 is a closed loop in which the working fluid F can be circulated. It contains a first compressor unit 21 for compressing the working fluid F and supplying a compressed working fluid F to the medium heating unit 14 (heat discharge section of the recuperator).

[0031] Fluidly downstream of the medium heating unit 14 an expander unit 22 is connected. The expander unit 22 can have one or more expander stages. In the present example a two-stage expander unit 22 is provided comprising a first expander device 23 and a second expander device 24.

[0032] As also shown in figure 1 in the present example, a heat discharge section of a first heat exchanger 26 and preferably a recuperator is fluidly connected downstream of the medium heating unit 14 and upstream of the expander unit 22 and in the example upstream of the first expander device 23. Downstream of the first expander device 23 a heat charging section of a second heat exchanger 27, preferably a recuperator, is fluidly connected in the heat pump cycle 16. At least a portion of the working fluid F of the heat pump cycle 16 flows downstream of the medium heating unit 14 through the heat discharge section of the first heat exchanger 26, the first expander device 23, the heat charging section of the second heat exchanger 27 and further via a heat charging section of the first heat exchanger 26 back to the low pressure and/or low temperature inlet side of the first compressor unit 21. Another portion of the working fluid F flows from the heat discharge section of the first heat exchanger 26 via a heat discharge section of the second heat exchanger 27 an through the second expander device 24 and a water-to-fluid heat exchanger 36.

[0033] The fluid flows and connections within the heat pump cycle 16 are particularly shown in figure 2. Downstream of the heat discharge section of the first heat exchanger 26 a first fluid valve 28 is provided that is connected with a first expander fluid line 29 and a second expander fluid line 30. The first expander fluid line 29 is connected with the high pressure side of the first expander device 23 and the second expander fluid line 30 is connected with the high pressure side of the second expander device 24 via the heat discharge section of the second heat exchanger 27. The low pressure outlet side of both temperature expander devices 23, 24 are connected with respective inlet ports of a second fluid valve 31 that is upstream of the heat charging section of the second heat exchanger 27. A heat charging section of the water-to-fluid heat exchanger 36 is fluidly connected between the outlet of the second expander device 24 and the second fluid valve 31.

[0034] The mass flow of the split streams of the working fluid F that leave the first fluid valve 28 are adjusted by means of this first fluid valve 28 so that the temperature of the streams of the working fluid F that reach the second fluid valve 31 have the same temperature.

[0035] In the example according to figure 2 the working fluid F is at a high temperature and a high pressure level downstream of the first compressor unit 21 and upstream of the medium heating device 14, e.g. at 470°C and at about 200 bar. After transferring heat to the thermal medium M when flowing through the medium heating unit 14, the temperature of the working fluid F in the heat pump cycle 16 is reduced, e.g. to about 300°C. When further flowing through the heat discharge section of the first heat exchanger 26, the temperature of the working fluid F is further decreased at the inlet of the first expander device 23 to for example 170°C. The portion of the working fluid flowing through the second expander fluid line 30 toward the low pressure expander device 24 flows through the heat discharge section of the second heat exchanger 27 thereby transferring heat to the working fluid F downstream of the expander unit 22 and in the present example downstream of the two expander devices 23, 24 (i.e. the second fluid valve 31 in the present example). In this embodiment the temperature at the inlet (high pressure) side of the second expander device 24 can be about 60°C to 65°C. The pressure of the working fluid F at the high pressure inlet sides of the expander unit 22 and the expander devices 23, 24 respectively corresponds to the pressure at the high pressure outlet side of the first compressor unit 21.

[0036] In the present example the pressure of the working fluid F is reduced in the expander unit 22 to about 45 to 50 bar. The temperature of the working fluid F at the outlet of the first expander device 24 can be in the range of 50°C to 55°C and the temperature at the outlet of the second expander device 24 can be in the range of about 10°C 15°C in the present example. The temperature of the working fluid F from the second expander device 24 is subsequently increased by means of the water-to-fluid heat exchanger 36 to the working fluid temperature level at the outlet of the first expander device 23 before being mixed at the second fluid valve 31. Downstream of the second fluid valve 31 the working fluid temperature is increased via the heat charging sections of the second and first heat exchangers 27, 26. Downstream of the second heat exchanger 27 and upstream of the first heat exchanger 26 the temperature of the working fluid can be about 130°C to 140°C and downstream of the first heat exchanger 26 at the low pressure inlet side of the first compressor unit 21 the temperature of the working fluid F can be about 280°C to 300°C at a pressure of about 45 to 50 bar.

[0037] The first compressor unit 21 is driven by means of an electric motor 38. The electric motor 38 can be used to drive a common shaft 39 for driving the first compressor unit 21 and the expander unit 22, as schematically illustrated in figures 1 and 2.

[0038] As already explained above the working fluid F of the heat pump cycle 16 flowing downstream from the expander unit 22 and in the present example from the second expander device 24 is routed through the water-to-fluid heat exchanger 36. The water-to-fluid heat exchanger 36 can be a recuperator. The water-to-fluid heat exchanger 36 is adapted to transfer heat from water W, that can be circulated in a water storage cycle 37, to the working fluid F of the heat pump cycle 16.

[0039] The water storage cycle 37 contains a hot water tank 40, a hot water pump 41 adapted to supply hot water W from the hot water tank 40 to an input 42 of a controllable valve unit 43. The controllable valve unit 43 has a first outlet 44 and a second outlet 45. The first outlet 44 is fluidly connected via the water-to-fluid heat exchanger 36 with a cold water tank 46. By means of a cold water pump 47 cold water W from the cold water tank 46 can be supplied via a third fluid valve 48 to a fluid-to-water heat exchanger 49. The fluid-to-water heat exchanger 49 is adapted to transfer heat from a working fluid F, that can be circulated in the turbine cycle 17, to the water W supplied from the cold water tank 46. The downstream side of the fluid-to-water heat exchanger 49 is connected with the hot water tank 40.

[0040] The second outlet 45 of the controllable valve unit 43 is fluidly connected with another inlet of the second fluid valve 48 via an air-cooled water cooling unit 50 that is cooled by ambient air. The amount or flow of hot water W supplied from the hot water pump 41 can be distributed arbitrarily between the first and second outlets 44, 45 of the controllable valve unit 43. Accordingly hot water W from the hot water tank 40 can either flow through the water-to-fluid heat exchanger 36 toward the cold water tank 46 or either through the water cooling unit 50 via the third fluid valve 48 toward the fluid-to-water heat exchanger 49.

[0041] In an alternative embodiment it would also be possible to omit the third fluid valve 48 or to locate the third fluid valve 48 downstream the water-to-fluid heat exchanger 36 and upstream the cold water tank 46. The downstream port of the water cooling unit 50 could also be connected with the cold water tank 46.

[0042] The controllable valve unit 43 can be a controllable 3-way valve or a combination of two 2-way valves, for example. It is preferably controlled by means of a control unit 51 for adjusting the output flow rates out of the respective outlets 44 and 45. For adjusting the controllable valve unit 43 the control unit 51 transmits a control signal S to the controllable valve unit 43. The control unit 51 may also control the pumps and/or the electric motor 38 and/or any other component or subsystem of the system 10.

[0043] At least one input signal can be provided to the control unit 51 based on which the control signal S can be calculated or determined. Particularly parameters characterizing the operating condition of the system 10 and/or parameters describing the actual environmental condition and/or parameters describing the forecast environmental condition can be used as input for the control unit 51. In the present example particularly at least one input signal characterizing the actual ambient air temperature Ta and/or a forecast ambient air temperature Tf can be submitted as input to the control unit 51.

[0044] The turbine cycle 17 is in the example of figures 1 and 2 a closed loop. It contains turbine unit 55 downstream of the medium cooling unit 15. The turbine unit 55 is adapted to create electrical energy. The flow of a working fluid F can be used to drive a turbine shaft 56 of a turbine 57, preferably a gas turbine. The rotation of the turbine shaft 56 can be used to drive a generator 58 of the turbine unit 55 in order to create electric power.

[0045] In the turbine cycle 17 downstream of the low pressure side of the turbine 57, the working fluid F is cooled and in this embodiment flows through a heat discharge section of a third heat exchanger 59 and/or through a heat discharge section of a fourth heat exchanger 60. The heat exchangers 59, 60 are preferably recuperators. Downstream of the heat discharge section of the fourth heat exchanger 60 a fourth fluid valve 61 is provided to distribute the flow of working fluid F into a first flow directly toward a second compressor unit 62 and a second flow routed via the heat discharge section of the fluid-to-water heat exchanger 49 toward the second compressor unit 62. In the present example the second compressor unit 62 comprises multiple compressor stages or devices and for example a first compressor device 63 and a second compressor device 64. The first compressor device 63 receives at its low pressure inlet side the first flow directly from the fourth fluid valve 61 and the second compressor device 64 receives at its low pressure inlet side the second flow from the fourth fluid valve 61 that is cooled via the fluid-to-water heat exchanger 49. The second compressor unit 62 is in the present example driven by means of the turbine shaft 56.

[0046] The high pressure outlet side of the second compressor unit 62 is fluidly connected with the heat charging section of the third heat exchanger 59. The high pressure outlet of the first compressor device 63 is directly fluidly connected with the heat charging section of the third heat exchanger 59, whereas the high pressure outlet of the second compressor device 64 is fluidly connected with the heat charging section of the third heat exchanger via the heat charging section of the fourth heat exchanger 60.

[0047] In a preferred embodiment the temperature of the working fluid F at the downstream side of the medium cooling unit 15 is about 430°C to 470°C and preferably 450°C at a pressure of about 230 to 250 bar, preferably 240 bar. After being routed through the turbine 57, the temperature of the working fluid F is decreased to about 310°C, for example, and the pressure is for example decreased to about 65-70 bar. From the low pressure outlet side of the turbine 57 the working fluid F flows through the heat discharge section of the third heat exchanger 57, thereby discharging heat down to a temperature of 200°C, for example, and by being further routed through the heat discharge section of the fourth heat exchanger 60, the temperature of the working fluid can be decreased down to about 65°C to 70°C at the inlet of the fourth fluid valve 61. The second fluid flow routed through the fluid-to-water heat exchanger 49 transfers heat toward the water W and its temperature is increased at the low pressure input side of the second compressor device 64 down to e.g. 25°C to 30°C.

[0048] The working fluid F flowing through the first compressor device 63 increases its temperature and its pressure up to e.g. 190°C at about 240 bar before being routed through the heat charging section of the third heat exchanger 59 in which its temperature is further increased before being routed through the medium cooling unit 15, e.g. to 280°C. At the high pressure outlet of the second compressor device 64 the temperature and the pressure of the working fluid F is increased to about 55°C to 60°C at a pressure of about 240 bar before entering the heat charging section fourth heat exchanger 60, in which the temperature of the working fluid F flowing toward heat charging section of the third heat exchanger 59 is increased to about same temperature and pressure level as the high pressure output side of the first compressor device 63.

[0049] Further in the present example the thermal medium, particularly the molten salt, stored in the hot medium reservoir has a temperature of about 460°C and the temperature of the thermal medium stored in the cold medium reservoir is about 290°C.

[0050] The water W of the water storage cycle 37 has a temperature of about 60°C in the hot water tank. The temperature of the water stored in the cold water tank is at about 19°C. The water W cooled by means of the air-cooled water cooling unit 50 has a temperature that is above the actual ambient air temperature Ta in the environment of the air-cooled water cooling unit 50. Depending on the actual ambient air temperature Ta, the temperature of the water W at the downstream outlet side of the water cooling unit 50 can be about 10°C higher than the actual ambient air temperature Ta.

[0051] As schematically shown in the embodiment of the system according to figures 7 and 8 it is also possible to integrate the heat pump circuit 16 and the turbine circuit 17 in order to reduce the number of heat exchanging units, if the working fluid F used in the heat pump circuit 16 and the turbine circuit 17 is the same. The electric motor 38 and the generator 58 may be realized as one motor-generator-unit 38, 58. The medium heating unit 14 and the medium cooling unit 15 may be physically identical units or recuperators and/or the first heat exchanger 26 and the third heat exchanger 59 may be physically identical heat exchangers or recuperators and/or the second heat exchanger 27 and the forth heat exchanger 60 may be physically identical heat exchangers or recuperators and/or the water-to-fluid heat exchanger 36 and fluid-to-water heat exchanger 49 may be physically identical heat exchangers or recuperators. This is possible because by adjusting the operational parameters, particularly the temperature and/or the pressure and/or mass-flow, in the system 10 so that the heat exchanging units or heat exchangers can be similar as indicated above. In order to allow the integration of two of the heat exchanging units as shown in figures 1 and 2 into one single unit as shown in figures 7 and 8, a valve arrangement 70 with a plurality of controllable valves 71 is provided. In the present example the valve arrangement 70 comprises six valves 71 arranged in the fluid connections of the fluid lines that define the integrated heat pump and turbine circuit 16, 17. The valves 71 can be controlled by means of the control unit 51 or another controlling device. The valves 71 are schematically illustrated by means of rectangles and maybe realized in any suitable known fluid valve configuration.

[0052] The dashed lines shown in figures 7 and 8 show the blocked fluid passages, in which no working fluid F flows because of the switching position of the valves 71 of the valve arrangement 70. The solid or continuous lines illustrate the fluid connections, which allow a flow of working fluid F. Thus in the condition of the system 10 shown in figure 7, the heat pump cycle 16 is active and the flow of working fluid F corresponds to the flow of working fluid F through the heat pump cycle 16 as shown in figures 1 and 2. In the condition of the system 10 shown in figure 8, the turbine cycle 17 is active and the flow of working fluid F shown in figure 8 corresponds to the flow of working fluid F through the turbine cycle 17 shown in figures 1 and 2. The flow of the working fluid F thus corresponds either to the flow of the working fluid F in the heat pump circuit 16 (solid lines in figure 7) or to the flow of the working fluid F in the turbine circuit 17 (solid lines in figure 8), depending whether thermal energy is to be stored or extracted from the thermal medium of the medium storage circuit 11.

[0053] In the following the function of the system 10 in the embodiment of figures 1 and 2 or either of figures 7 and 8 is described in more detail. The system 10 described so far works as follows:

[0054] If a power plant, e.g. a power plant containing solar panels and/or wind turbines, creates an excess of electric power that is not required by an electric load or a power grid, the excess electric power can be stored in the form of thermal energy in the system 10 according to the present invention. In such a case the excess electric power is used to drive the electric motor 38. In the heat pump cycle 16 the working fluid F is circulated and heated and compressed by means of the first compressor unit 21. The thermal energy of the working fluid F is transferred by means of the medium heating unit 40 at least partly to the thermal medium M circulating in the medium storage cycle 11. The heated thermal medium is stored in the hot medium reservoir 12. Concurrently the water W that circulates in the water storage cycle 37 transfers heat to the working fluid F of the heat pump cycle 16 by means of the water-to-fluid heat exchanger 36. Accordingly when electric energy is transferred into thermal energy the hot water tank 40 is discharged and the cold water tank 46 is filled.

[0055] On the other hand if the load or the grid requires additional electric power, thermal medium M from the hot medium reservoir 12 is supplied toward the cold medium reservoir 13 and thereby, via the medium cooling unit 15, transfers heat to the working fluid F circulating in the turbine cycle 17. The heated working fluid F is supplied to the turbine unit 55, expands in the turbine 57 and thereby creates rotational energy that is converted by means of the generator 58 into electric energy that can be supplied to the load or grid. The working fluid F circulating in the turbine cycle 17 is cooled by means of the fluid-to-water heat exchanger 49 that transfers heat from the working fluid F of the turbine cycle to the water W circulating in the water storage cycle 37 so that the cold water tank 46 is discharged and the hot water tank 40 is filled.

[0056] The efficiency of the heat pump cycle 16 and the turbine cycle 17 is different. This means that if a certain amount of thermal energy (heat) is drawn from the thermal medium M in order to produce electric energy by means of the turbine cycle 17, a certain water volume is discharged from the cold water tank 46 in order to cool the working fluid F of the turbine cycle 17. In the operating condition of the system 10 where the heat pump cycle 16 transfers thermal energy (heat) to the thermal medium M of the medium storage cycle 11, a certain water volume is discharged from the hot water tank in order to transfer heat by means of the water-to-fluid heat exchanger 36 from the water W to the working fluid F of the heat pump cycle 16. The volumes of water W taken from the respective tanks 40, 46 in the described operating conditions are different even though the thermal energy of the thermal medium M is maintained at a constant level, so that the cold water tank 46 might not fill up at the same rate as the hot water tank 40 and over time, the cold water tank 46 will run empty. Accordingly the round trip efficiency of the system 10 is affected.

[0057] In order to overcome this problem, the air-cooled water cooling unit 50 is provided. Water W can be discharged from the hot water tank 40, routed via the air-cooled water cooling unit 50 to the fluid-to-water heat exchanger 49 in order to cool the working fluid F of the turbine cycle 17. This air-cooled water cooling unit 50 works independent from the operation of the heat pump cycle 16 and thus provides additional flexibility. The amount of water flowing through the water-to-fluid heat exchanger 36 and air-cooled water cooling unit 50 can be controlled by means of the controllable valve unit 43 that is controlled by the control unit 51.

[0058] This structure further provides the possibility to prepare the system 10, if e.g. a warm day is forecast in which the ambient air temperature is relatively warm.

[0059] Reference is now made to exemplary conditions of the system 10 that are schematically illustrated in figures 3-6 by way of example only. Other operating conditions can also occur and can be handled by the system 10. Figures 3-6 are provided to explain the advantages of the system 10 by way of example.

[0060] The controllable valve unit 43 supplies a first flow rate R1 of water W from the first output 44 to the water-to-fluid heat exchanger 36 and a second flow rate R2 from the second output 45 to the air-cooled water cooling unit 50. In an initial condition it is assumed that these flow rates R1, R2 have a predefined amount and can e.g. be equal as shown in figure 3. The water level of the cold water tank 46 is e.g. at a medium level, so that there is enough flexibility to increase the volume of cold water W in the cold water tank 46 and concurrently to take cold water W out of the cold water tank 46.

[0061] In the situation illustrated in figure 4 it is assumed that the actual ambient air temperature Ta is unexpectedly high. Accordingly, the air-cooled water cooling unit 50 cannot be used for cooling the water W. Thus the controllable valve unit 43 can only provide the first flow rate R1 toward the water-to-fluid heat exchanger 36 and decreases in the present example the second flow rate R2 down to zero. In this situation - as already explained above - on average the level in the cold water tank 46 cannot be maintained under the assumption that the amounts of energy converted from electric energy into thermal energy and from thermal energy converted into electric energy are equal on average (which is the case over a sufficiently long term period). Accordingly the water level in the cold water tank 46 decreases to an undesired low level, as illustrated in figure 4, and might run dry.

[0062] The system of the present invention is able to use a forecast temperature Tf of the ambient air in order to prepare the system 10 for operation on a forecast warm day. As shown in figure 5, the forecast temperature Tf on the next day or one of the following days is high, so that the air-cooled water cooling unit 50 will not be able to work as required to cool the water W. In such a situation, the control unit 31 controls the controllable valve unit 43 by means of the control signal S to increase the second flow rate R2 of water W directed from the hot water tank 40 over the air-cooled cooling water unit 50 for cooling the working fluid F circulating in the turbine cycle 17 (by means of the fluid-to-water heat exchanger 49). Accordingly the water W that has to be discharged from the cold water tank 46 decreases and the water level in the cold water tank 46 can be increased, as illustrated in figure 5.

[0063] Figure 6 now shows the operating condition on the forecast warm day. It can be seen that the air-cooled water cooling unit 50 cannot be used and that the second flow rate R2 is in the present example reduced to zero. As already explained, in such a situation the level of the cold water tank 46 decreases. But since the level of the cold water tank 46 has been increased before, the danger is avoided that the amount of cold water W provided in the cold water tank 46 is insufficient for operation to cool the working fluid F in the turbine cycle 17. In so doing at least a certain time period of warm weather (warm ambient air) can be maintained without any restrictions. Thus the flexibility and availability of the system 10 and the total efficiency is increased compared with conventional systems.

[0064] The present invention refers to a system 10 and a method of operating the system 10. The system 10 includes a heat pump cycle 16, a turbine cycle 17, a medium storage cycle 11 and a water storage cycle 37. By means of the heat pump cycle 16, heat of a working fluid F can be transferred to a thermal medium M for storing thermal energy. By means of the turbine cycle 17, heat of the thermal medium M can be transferred to a working fluid F. In so doing electric energy can be converted into thermal energy (heat of the thermal medium) or transferred from thermal energy (heat of the thermal medium) into electric energy by operating either the heat pump cycle 16 or the turbine cycle 17. The water storage cycle 37 is used to cool the working fluid F of the turbine cycle 17 and to heat the working fluid F of the heat pump cycle 16. The thermal coupling between the water storage cycle 37 and the heat pump cycle 16 is provided by means of a water-to-fluid heat exchanger 36 and the thermal coupling between the water storage cycle 37 and the turbine cycle 17 is provided by means of a fluid-to-water heat exchanger 49. The water storage cycle 37 additionally contains a preferably air-cooled water cooling unit 50 that can be operated independent from the water-to-fluid heat exchanger 36.

[0065] The present invention refers to a system 10 and a method of operating the system 10. The system 10 contains a heat pump cycle 16, a turbine cycle 17, a medium storage cycle 11 and a water storage cycle 37. By means of the heat pump cycle 16, heat of a working fluid can be transferred to a thermal medium (M) for storing thermal energy. By means of the turbine cycle 17, heat of the thermal medium (M) can be transferred to a working fluid (F). In so doing electric energy can be converted into thermal energy or transferred from thermal energy into electric energy by operating either the heat pump cycle 16 or the turbine cycle 17. The thermal coupling between the water storage cycle 37 and the heat pump cycle 16 is provided by means of a water-to-fluid heat exchanger 36 and the thermal coupling between the water storage cycle 37 and the turbine cycle 17 is provided by means of a fluid-to-water heat exchanger 49. The water storage cycle 37 additionally contains an air-cooled water cooling unit 50 that can be operated independent from the water-to-fluid heat exchanger 36.

Parts list:

[0066]

10	system
11	medium storage cycle
12	hot medium reservoir
13	cold medium reservoir
14	medium heating unit
15	medium cooling unit
16	heat pump cycle
17	turbine cycle
21	first compressor unit
22	expander unit
23	first expander device
24	second expander device
26	first heat exchanger
27	second heat exchanger
28	first fluid valve
29	first expander fluid line
30	second expander fluid line
31	second fluid valve
36	water-to-fluid heat exchanger
37	water storage cycle
38	electric motor
39	shaft
40	hot water tank
41	hot water pump
42	input of the controllable valve unit
43	controllable valve unit
44	first output of the controllable valve unit
45	second output of the controllable valve unit
46	cold water tank
47	cold water pump
48	third fluid valve
49	fluid-to-water heat exchanger
50	air-cooled water cooling unit
51	control unit
55	turbine unit
56	turbine shaft
57	turbine
58	generator
59	third heat exchanger
60	forth heat exchanger
61	forth fluid valve
62	second compressor unit
63	first compressor device
64	second compressor device
70	valve arrangement

71 valve

F working fluid
M thermal medium
S control signal
Ta actual air temperature
Tf forecast air temperature
W water

Claims

1. System (10) for converting electric energy into thermal energy and for storing thermal energy, comprising:

a heat pump cycle (16) in which a working fluid (F) can be circulated comprising a first compressor unit (21) for compressing the working fluid (F), an expander unit (22) for expanding the working fluid (F), and a medium heating unit (14) that are fluidly connected so that the medium heating unit (14) is fluidly connected downstream of the first compressor unit (21) and upstream of the expander unit (22), wherein a water-to-fluid heat exchanger (36) is fluidly connected to the heat pump cycle (16) downstream of the expander unit (22), wherein the medium heating unit (14) is adapted to heat a thermal medium (M) that can be circulated in a medium storage cycle (11), wherein the water-to-fluid heat exchanger (36) is adapted to transfer heat from water (W) that can be circulated in a water storage cycle (37) to the working fluid (F),
a turbine cycle (17) in which a working fluid (F) can be circulated comprising a turbine unit (55), a medium cooling unit (15) and a fluid-to-water heat exchanger (49) that are fluidly connected so that the medium cooling unit (15) is upstream of the turbine unit (55) and the fluid-to-water heat exchanger (49) is downstream of the turbine unit (55), wherein the medium cooling unit (15) is adapted to cool the thermal medium (M) of the medium storage cycle (11), wherein the fluid-to-water heat exchanger (49) is adapted to transfer heat from the working fluid (F) to the water (W) of the water storage cycle (37),
wherein the water storage cycle (37) comprises a hot water tank (40), a controllable valve unit (43) downstream of the hot water tank (40) having a first outlet port (44) and a second outlet port (45), and wherein the first outlet port (44) is fluidly connected via the water-to-fluid heat exchanger (36) with a cold water tank (46) and/or with the fluid-to-water heat exchanger (49) and the second outlet port (45) is fluidly connected via an water cooling unit (50) with the cold water tank (46) and/or with the fluid-to-water heat exchanger (49).

2. System of claim 1, wherein the water storage cycle (37) is a closed loop.

3. System of claim 1 or 2, wherein the water cooling unit (50) is air cooled by means of ambient air.

4. System of any of the preceding claims, wherein the medium storage cycle (11) is a closed loop comprising a hot medium reservoir (12) downstream of the medium heating unit (14) and a cold medium reservoir (13) downstream of the medium cooling unit (15).

5. System of any of the preceding claims, wherein the first compressor unit (21) is driven by means of an electric motor (38).

6. System of any of the preceding claims, wherein the turbine cycle comprises a second compressor unit (62) that is driven by means of a turbine rotor or shaft (56) of the turbine unit (55).

7. System of any of the preceding claims, wherein the heat pump cycle (16) comprises a first heat exchanger (26) that has a heat discharge section that is fluidly connected downstream of the medium heating unit (14) and upstream of the expander unit (22).

8. System of any of the preceding claims, wherein the expander unit (22) comprises a first expander device (23) and a second expander device (24).

9. System of claim 8, wherein downstream of the first heat exchanger (26) a first fluid valve (28) is provided for splitting the working fluid in two split streams, wherein one of the split streams is conducted to the first expander device (23) and the other of the split streams is conducted to the second expander device (24), and wherein a second fluid valve (31) is provided downstream of the first expander device (23) and the second expander device (24), that mixes the working fluid streams delivered from the two expander devices (23, 24).

10. System of claim 9, wherein the first fluid valve (28) is adjusted or controlled to adjust the mass flow of the split streams of the working fluid (F), such that the fluid streams delivered from the two expander devices (23, 24) have particularly a desired temperature and/or a desired pressure.

11. System of any of claims 7 to 10, wherein the first expander device (23) and/or the second expander device (24) is fluidly connected downstream of the heat discharge section of the first heat exchanger (26).

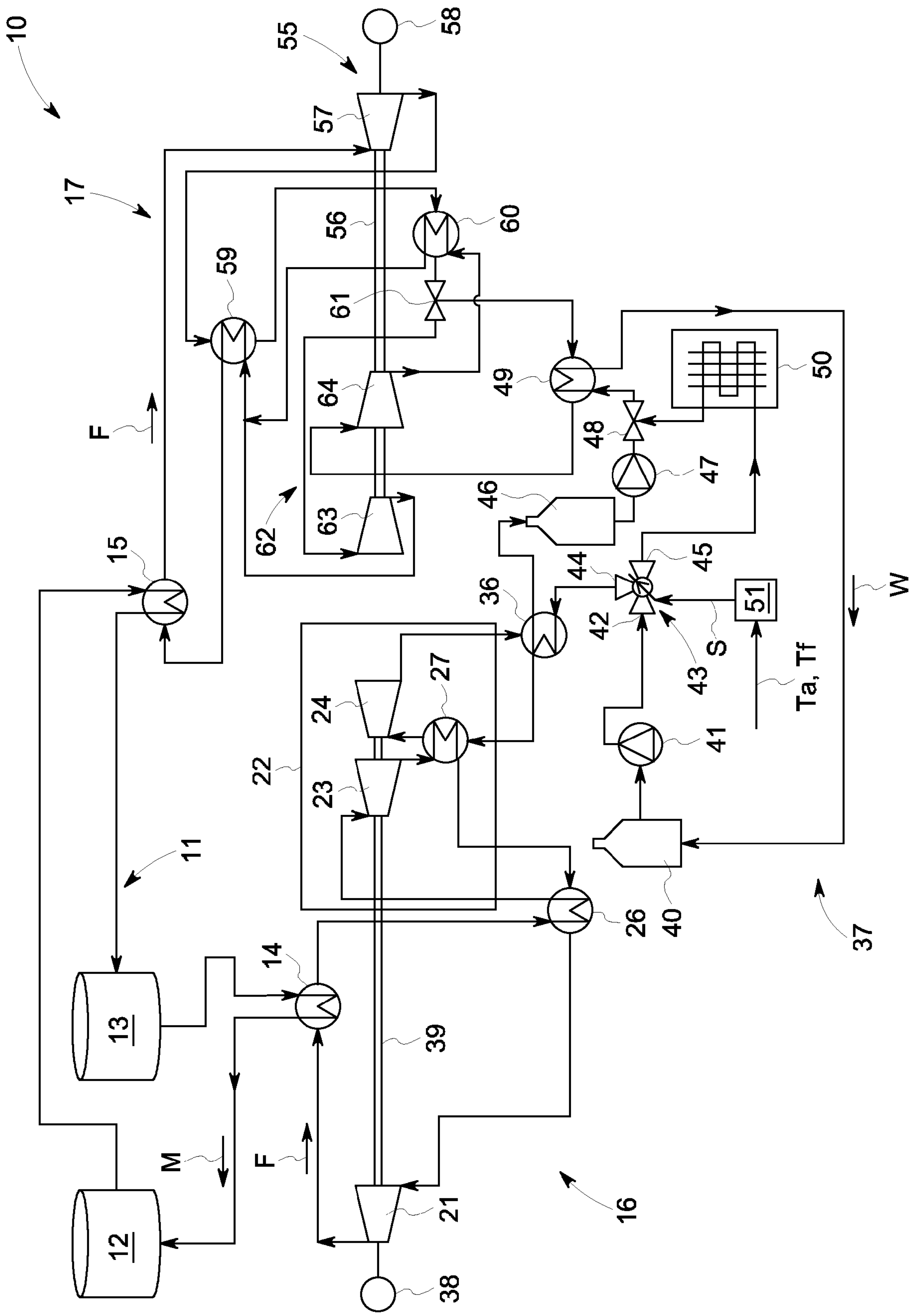
12. System of claim 7 and any of claims 8 to 11, wherein the heat pump cycle (16) comprises a second heat exchanger (27) has a heat discharge section that is fluidly connected downstream of the first heat exchanger (26) and upstream of the second expander device (24).

13. System of claim 12, wherein a heat charging section of the second heat exchanger (27) is fluidly connected downstream of the first expander device (23) and upstream of the heat charging section of the first heat exchanger (26).

14. System of any of the preceding claims, wherein a control unit (51) is present that is adapted to control the controllable valve unit (43) depending on at least one environmental parameter (Ta, Tf).

15. Method of operating a system according to any of the preceding claims, comprising the following steps:

- if electrical energy shall be stored in form of thermal energy: driving the first compressor unit (21) in order to transfer heat from the working fluid (F) of the heat pump cycle (16) to the thermal medium (M) of the medium storage cycle (11);
- if electrical energy shall be produced by the turbine unit (55): transferring heat from the thermal medium (M) of the medium storage cycle (11) to the working fluid (F) of the turbine cycle (17), supplying working fluid (F) to operate the turbine unit (55) therby transfering heat from the working fluid (F) of the turbine cycle (17) to the water (W) of the water storage cycle (37) by means of the fluid-to-water heat exchanger (49), wherein the amount of water (W) supplied to the water-to-fluid heat exchanger (36) and/or the amount of water (W) supplied to the water cooling unit (50) is controlled by means of the controllable valve unit (43).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F
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Ta, Tf

FIG. 1

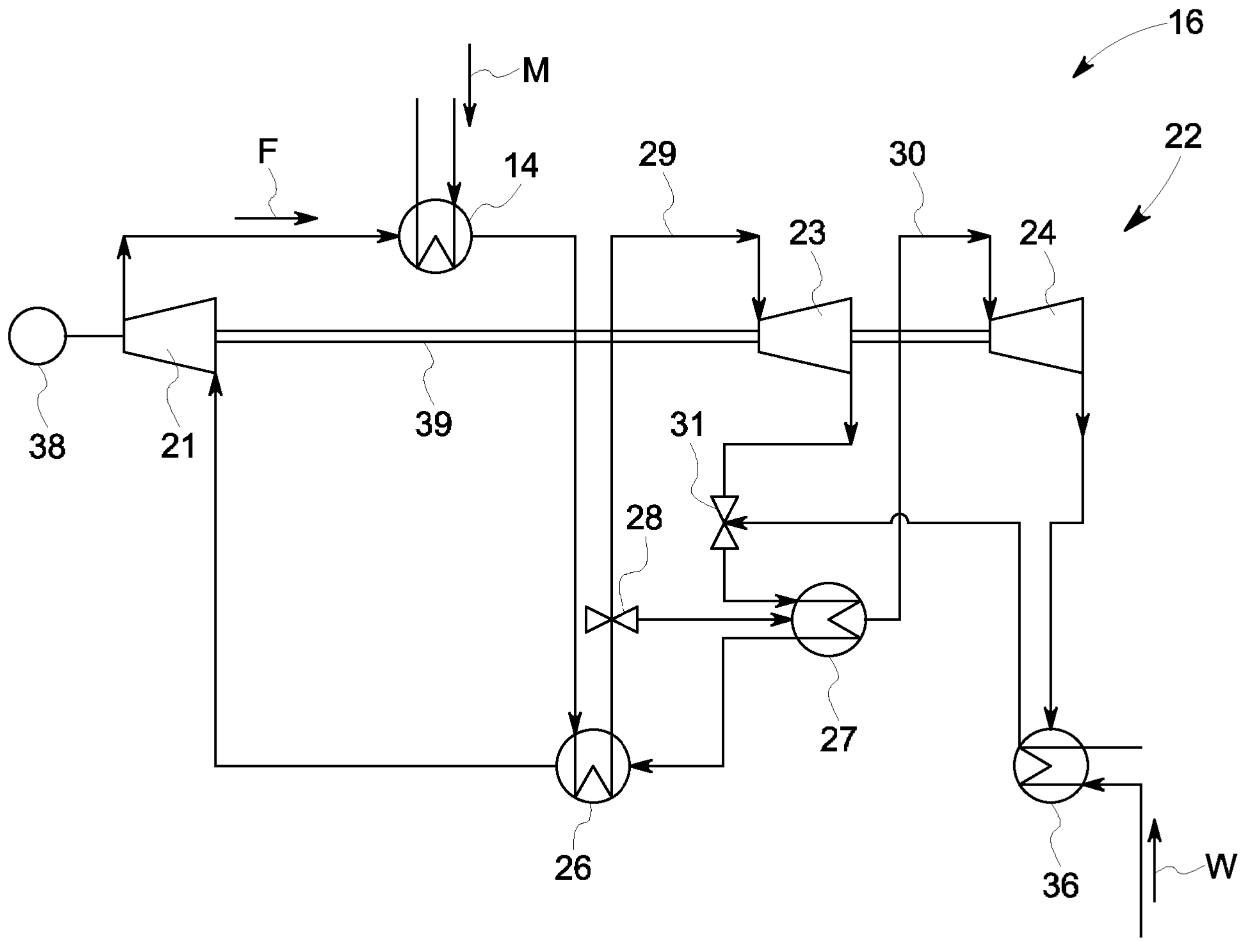
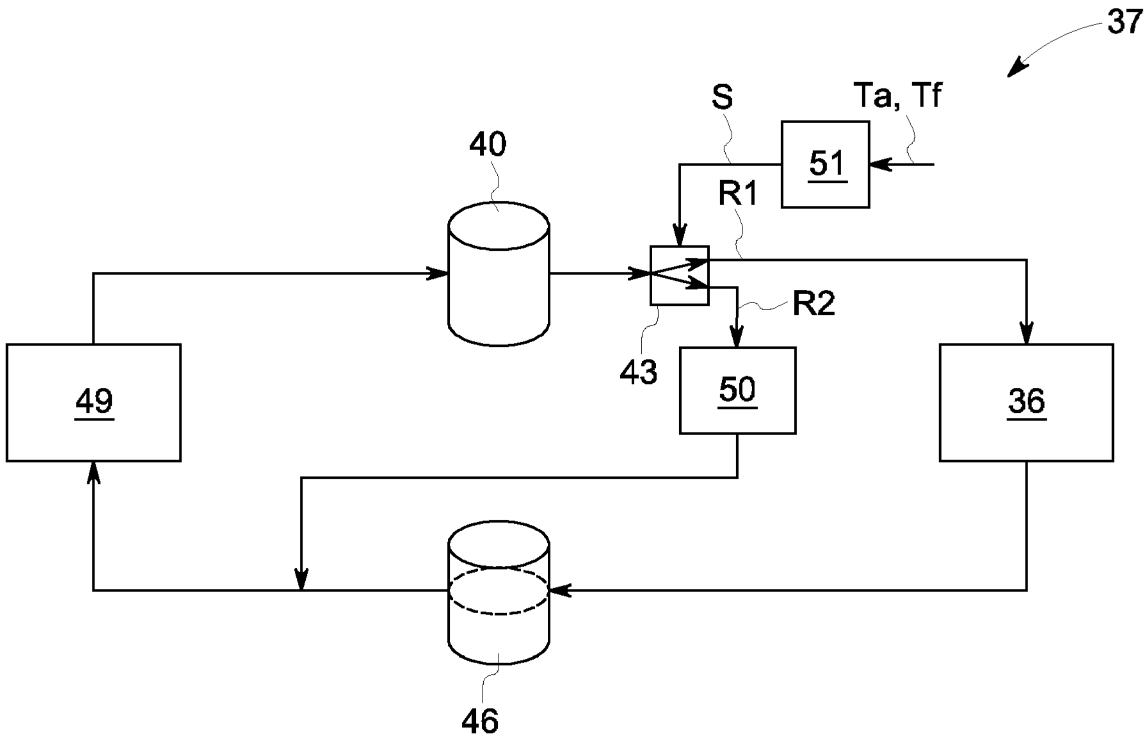


FIG. 2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R1
R2
43
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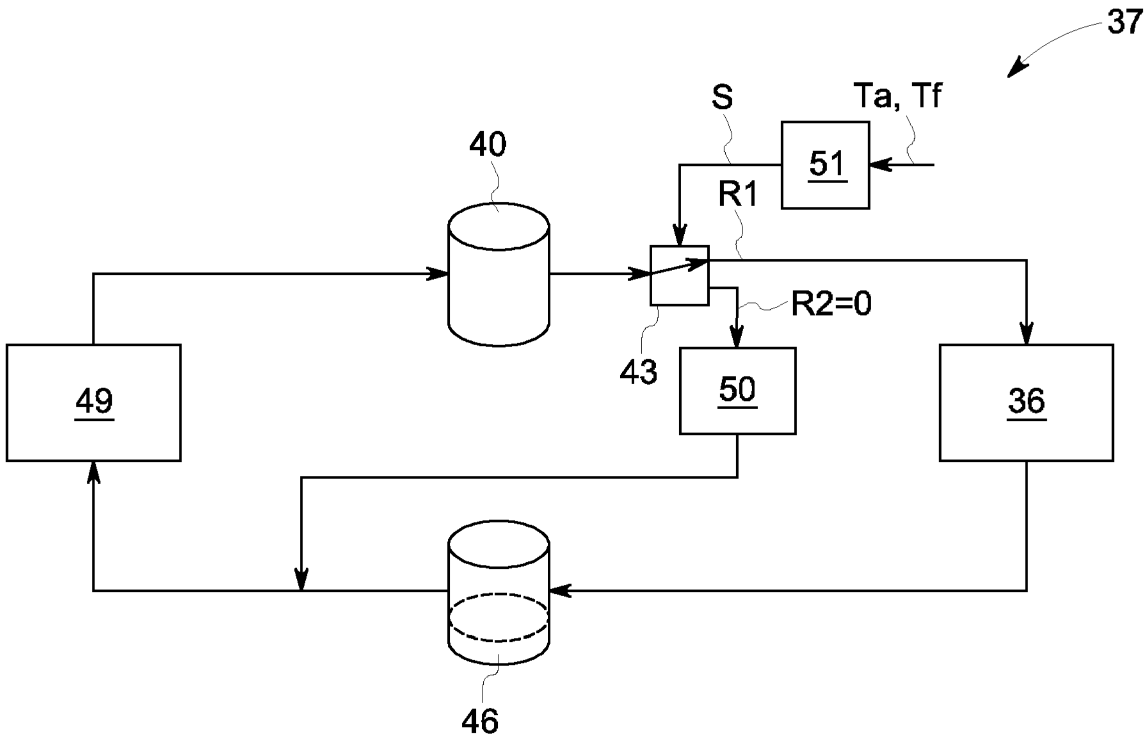
FIG. 3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Ta, Tf
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R1
R2=0
43
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36
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FIG. 4

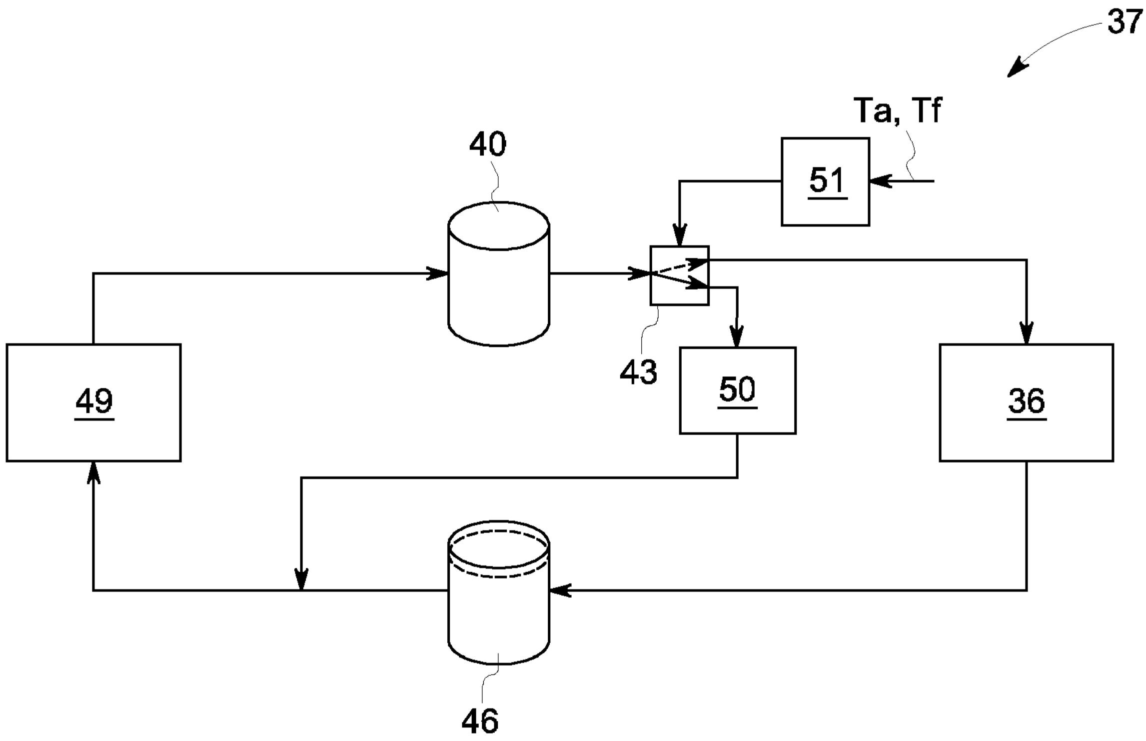

FIG. 5

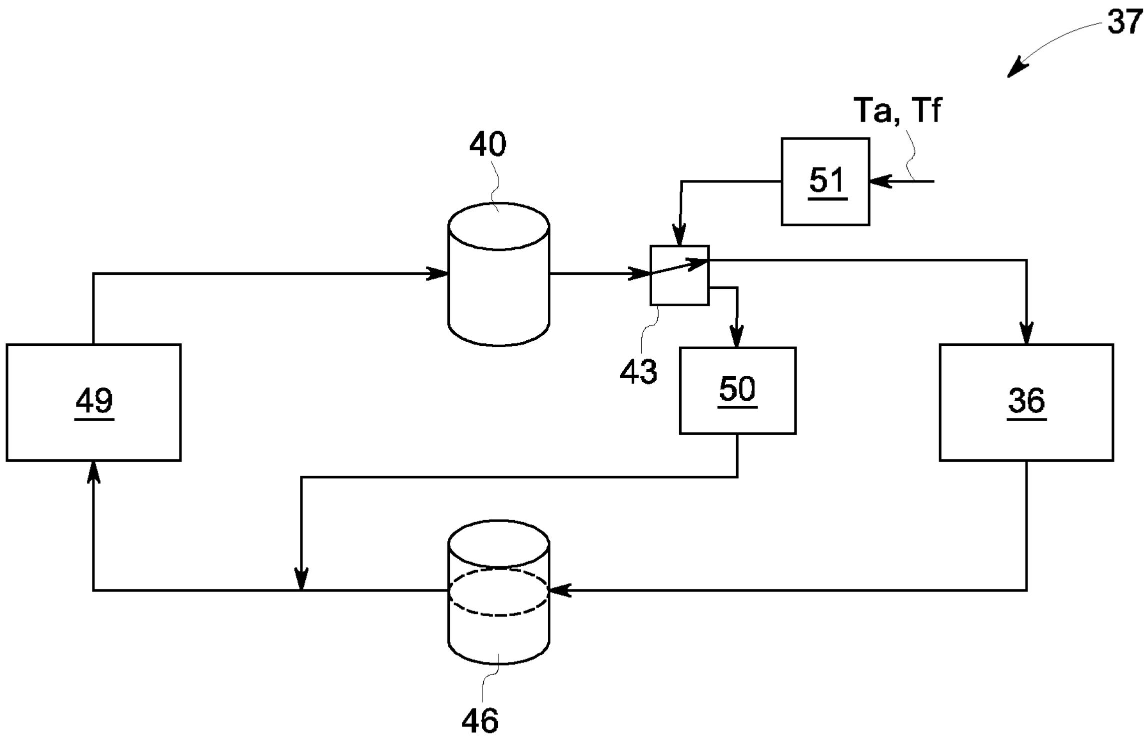

FIG. 6

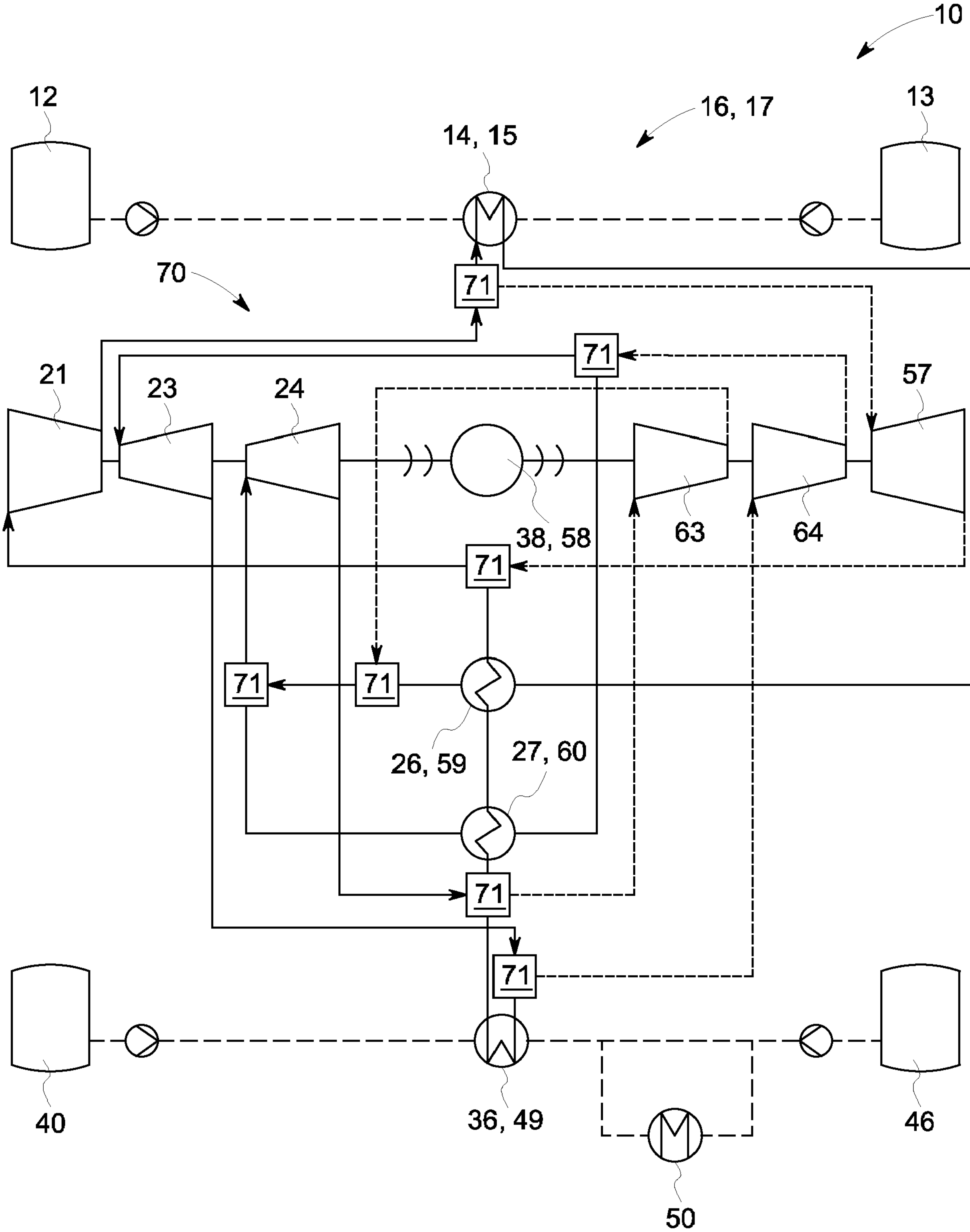
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FIG. 7

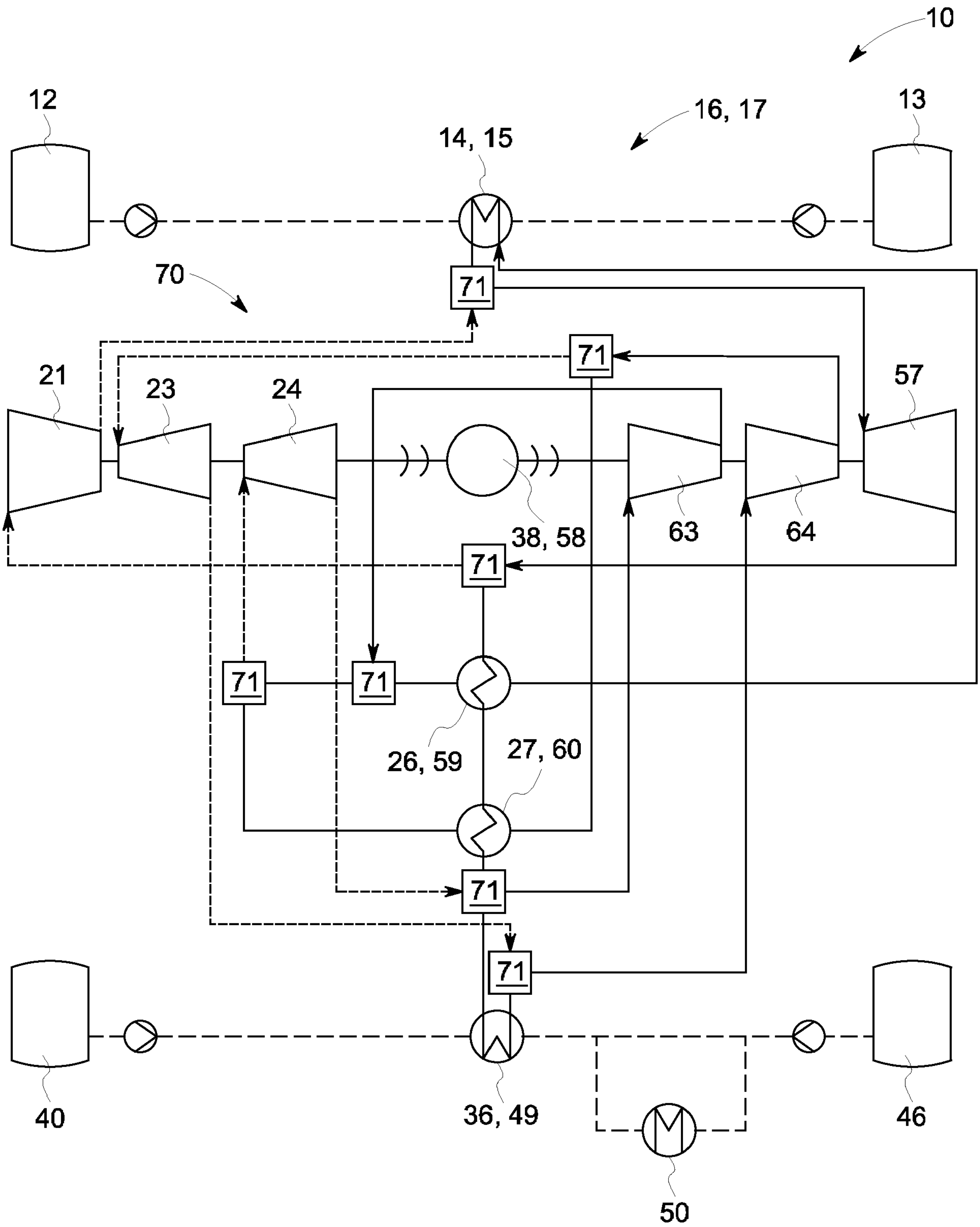
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FIG. 8

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EUROPEAN SEARCH REPORT

Application Number
EP 17 18 6774

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F01K
F25B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	21 February 2018	Röberg, Andreas

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