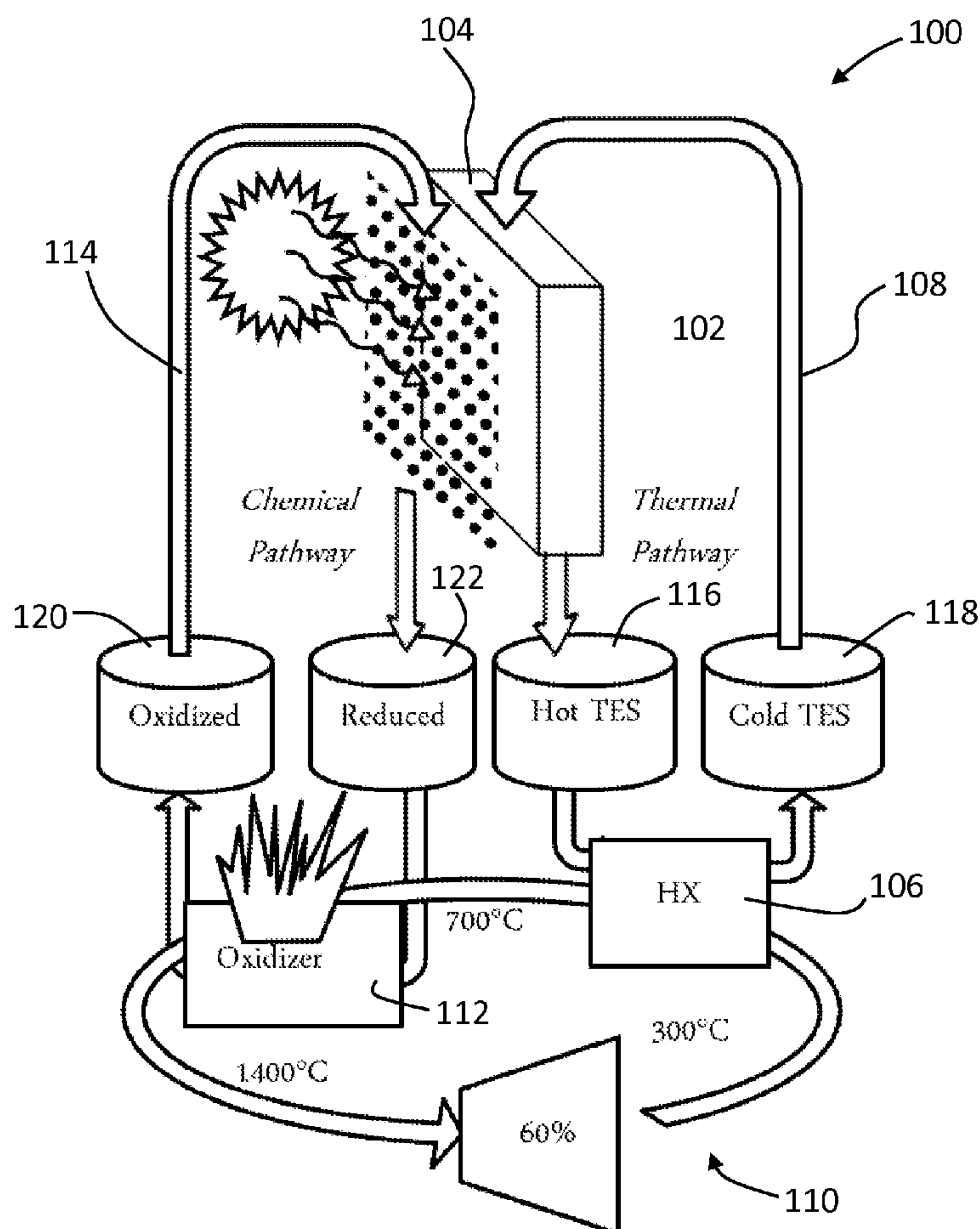


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Erickson et al.(10) **Pub. No.: US 2015/0253039 A1**(43) **Pub. Date: Sep. 10, 2015**(54) **COUPLED CHEMICAL-THERMAL SOLAR
POWER SYSTEM AND METHOD****Publication Classification**(71) Applicants: **Luke ERICKSON**, Lakewood, CO
(US); **Russell MUREN**, Boulder, CO
(US); **ABENGOA SOLAR INC.**,
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Russell Muren, Boulder, CO (US)(21) Appl. No.: **14/430,036**(22) PCT Filed: **Oct. 10, 2013**(86) PCT No.: **PCT/US13/64226**§ 371 (c)(1),
(2) Date:**Mar. 20, 2015****Related U.S. Application Data**(60) Provisional application No. 61/714,377, filed on Oct.
16, 2012.(57) **ABSTRACT**

A CSP system is disclosed which couples a thermal and a chemical energy pathway. The thermal pathway utilizes a heat transfer fluid to collect concentrated sunlight as thermal energy at medium temperature and transfer this energy to a thermal-to-electric power cycle. In parallel, the chemical pathway uses a redox material which undergoes direct photoreduction in the receiver to store the solar energy as chemical potential. This redox material is then oxidized at very high temperatures in the power cycle in series with the thermal pathway heat exchanger. This coupling allows the receiver to perform at the high efficiencies typical of state of the art thermal power towers while simultaneously achieving the power cycle efficiencies typical of natural gas combustion plants and achieving a very high overall solar-to-electric conversion efficiency.



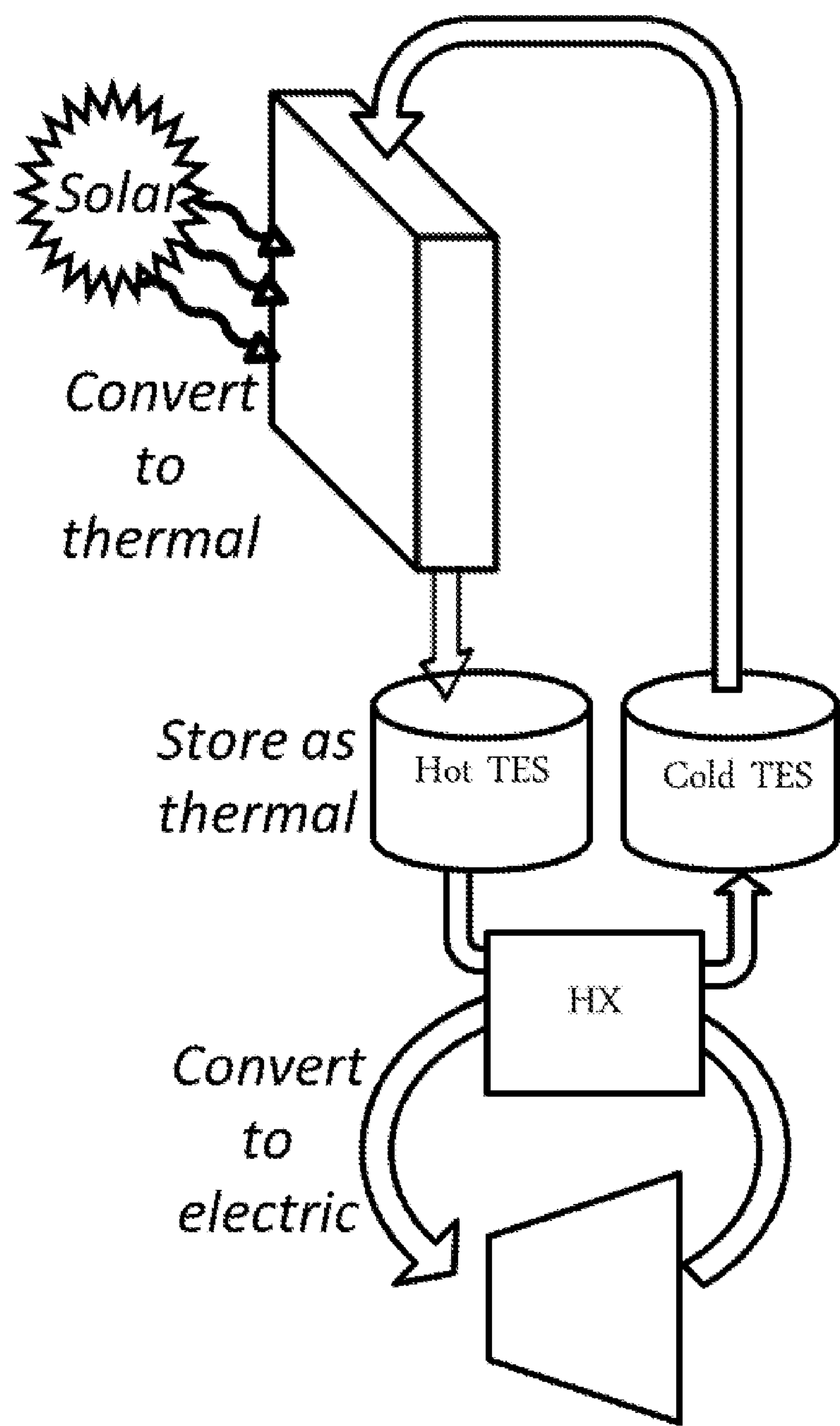


FIG. 1 (Prior Art)

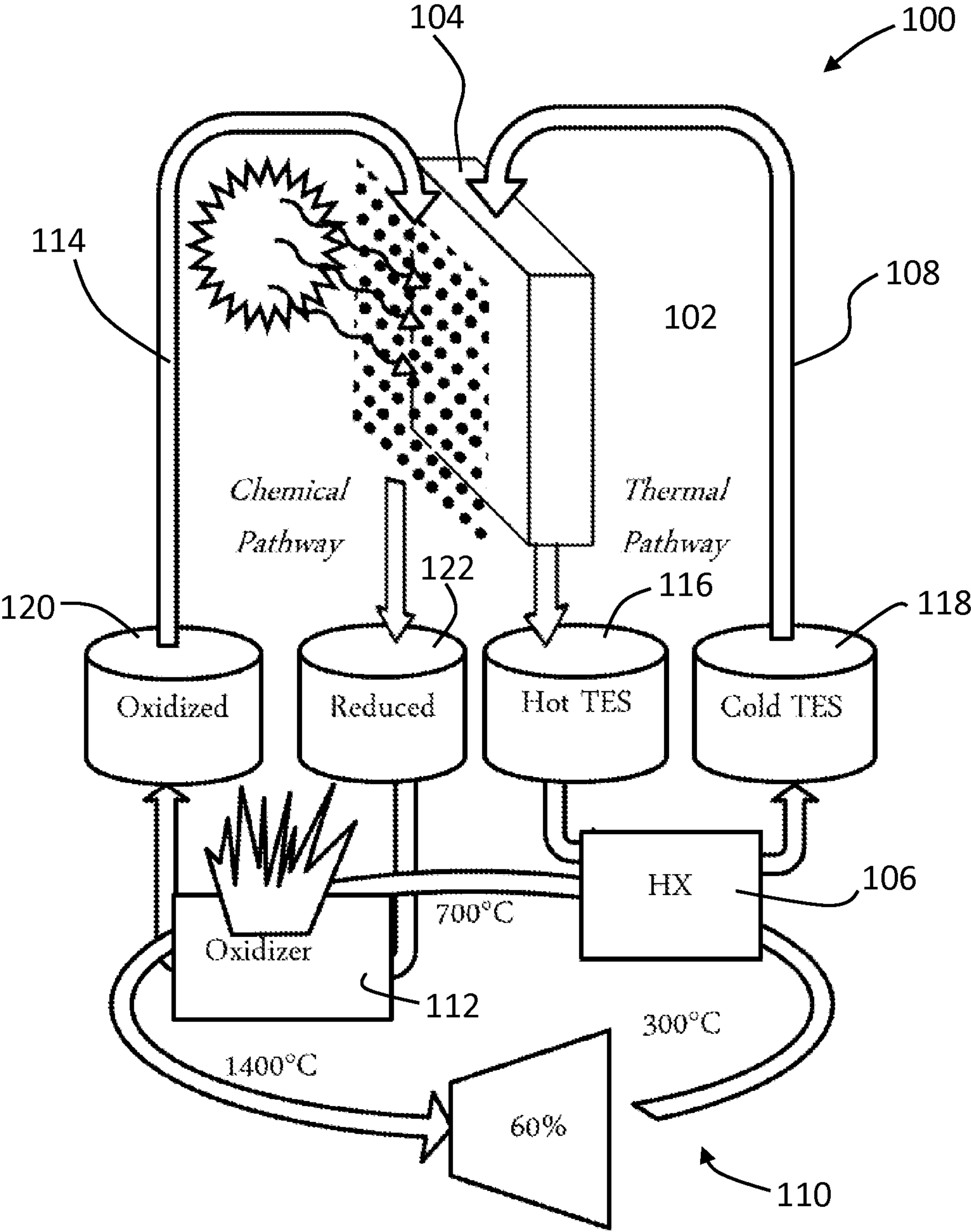


FIG. 2

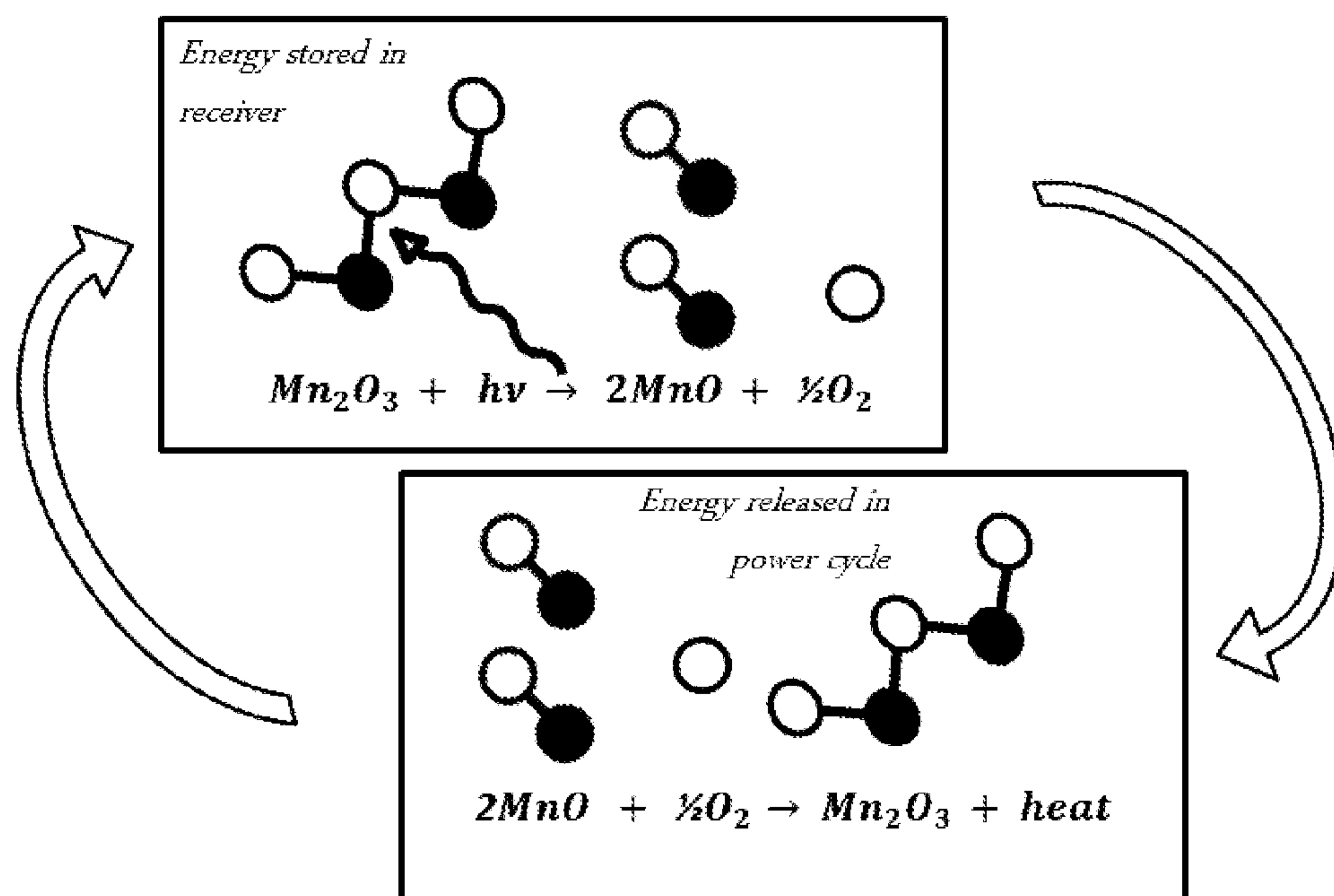


FIG. 3

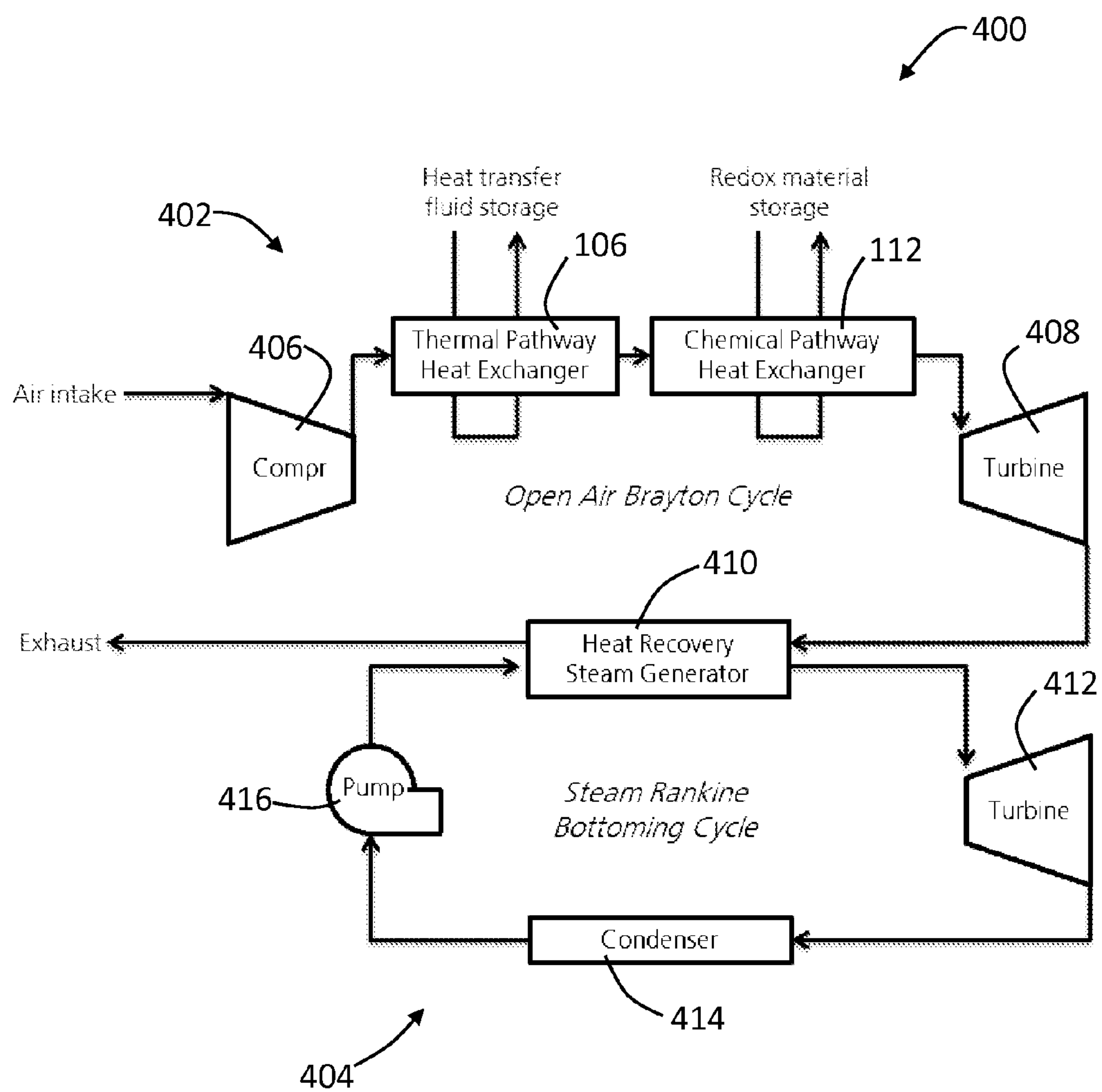


FIG. 4

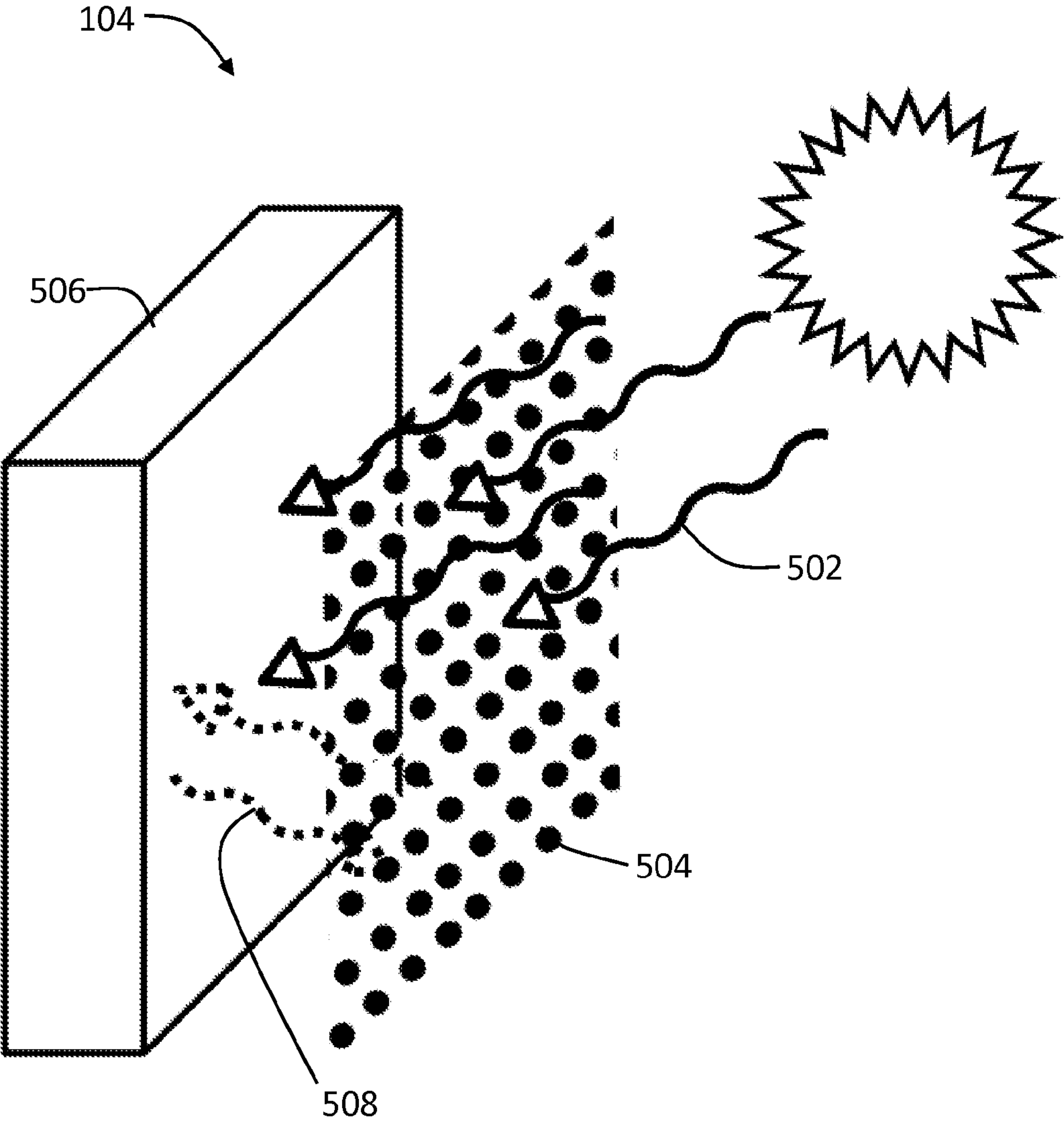


FIG. 5

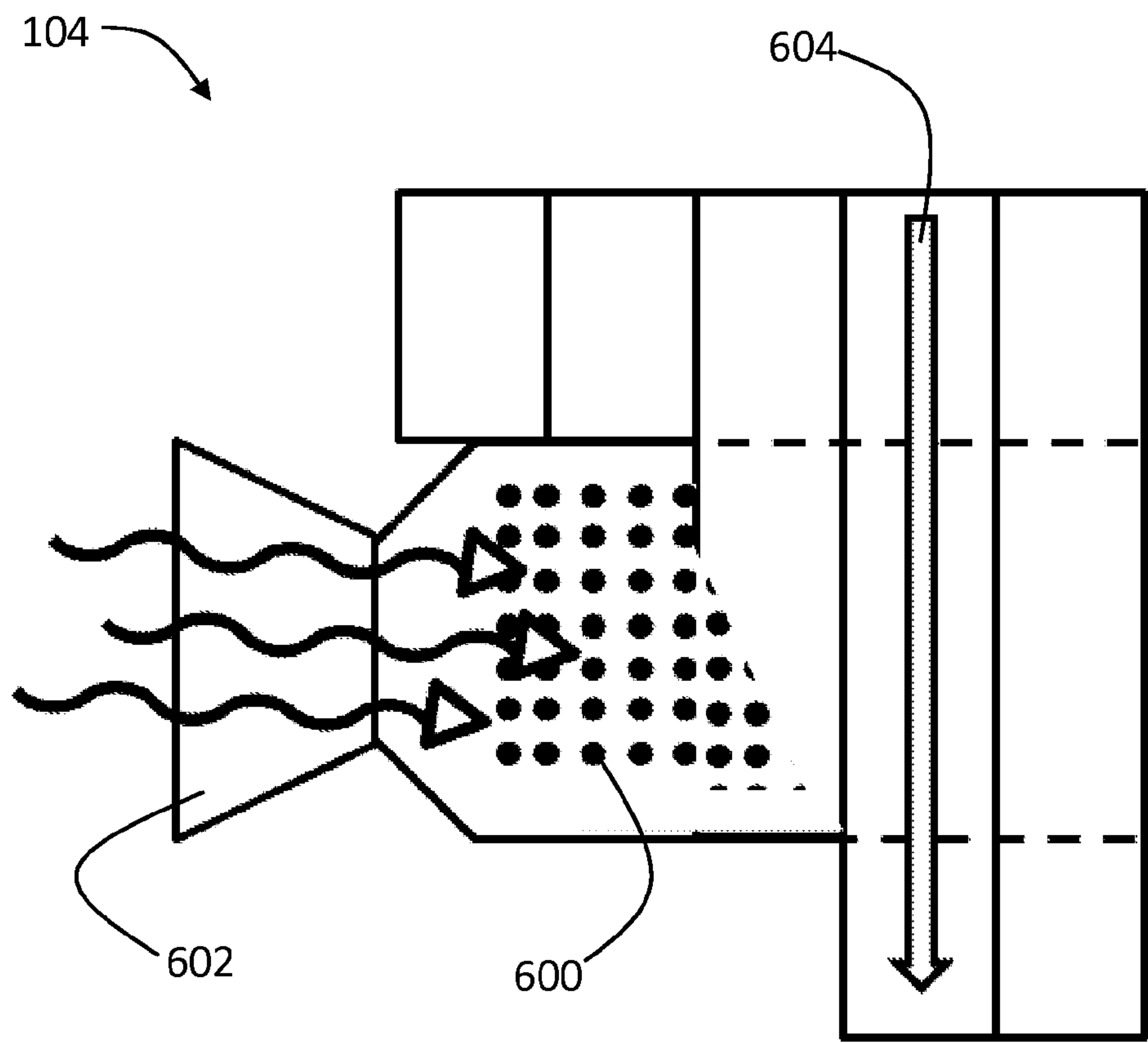


FIG. 6

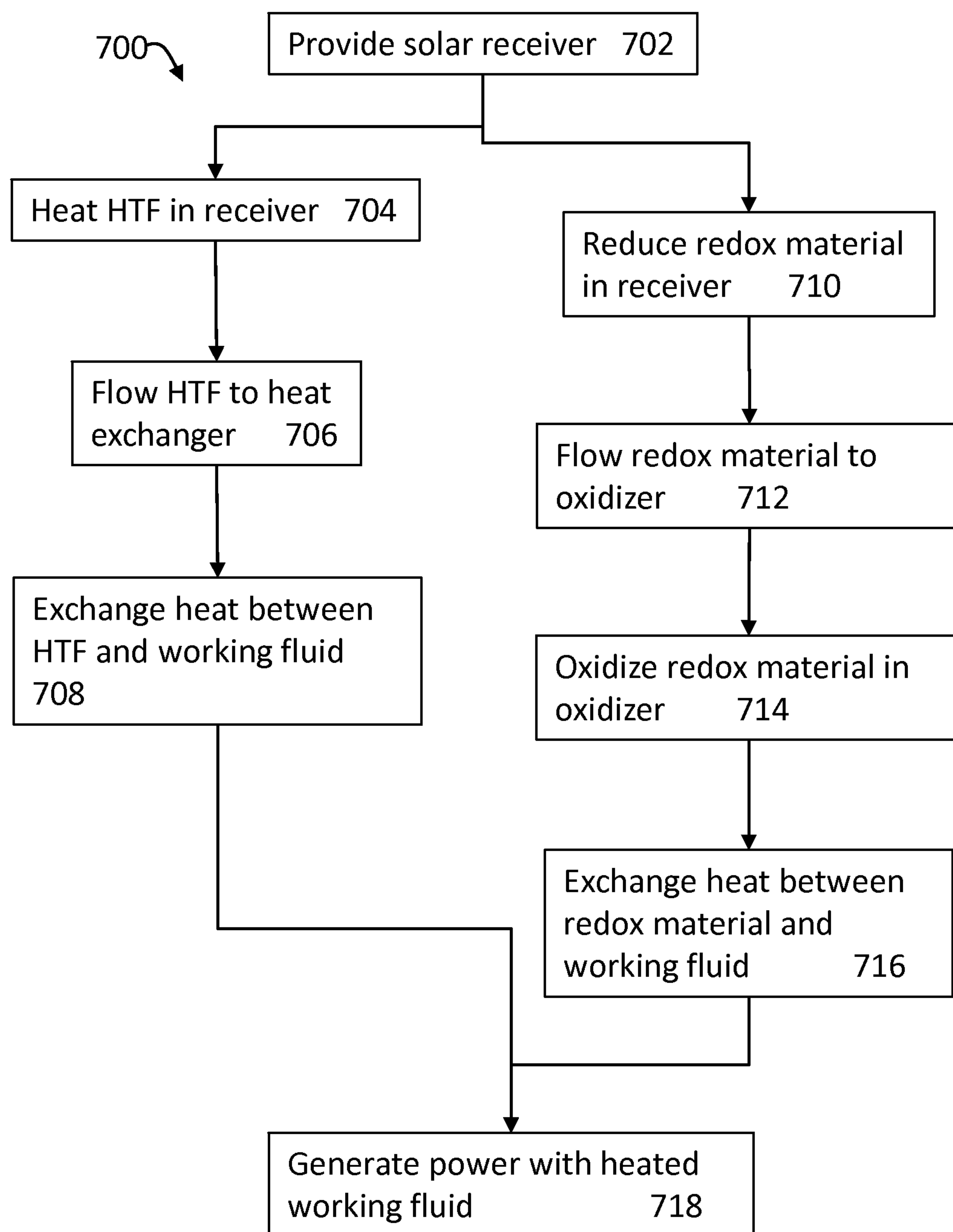


FIG. 7

COUPLED CHEMICAL-THERMAL SOLAR POWER SYSTEM AND METHOD

TECHNICAL FIELD

[0001] The embodiments disclosed herein include systems and methods in the field of concentrating solar power (“CSP”) generation, also known as solar thermal power generation. The disclosed systems and methods generally utilize two coupled parallel energy pathways, one thermal and one chemical, to convert solar energy to electrical energy at high efficiency. Specifically, the disclosed embodiments include a solar receiver in communication with separate chemical energy storage material and heat transfer fluid flowing or transported in separate pathways. The chemical energy storage material undergoes low temperature photoreduction at the receiver. In addition, heat transfer fluid (“HTF”) is heated to an operational temperature at the solar receiver. The chemical energy storage material and HTF are used to drive a power cycle which operates at relatively high temperatures because the chemical energy storage material is exothermically oxidized as, or in sequence with, the HTF being cooled.

BACKGROUND

[0002] Concentrating solar technologies may generally be divided into thermal systems for electric power generation and chemical systems for fuels production and chemical processing. Variations on thermal CSP plants are known in the art which utilize different types of reflector configurations such as troughs, dishes, and heliostat fields. Known CSP systems utilize many alternative heat transfer fluids such as oils, molten salts, and steam and can be used to drive various power cycles such as steam Rankine, supercritical steam Rankine, and supercritical carbon dioxide Brayton cycles.

[0003] The current state of the art in high-temperature CSP towers is represented by direct steam generation towers such as shown in US Patent Application 2008/0302314 and molten nitrate salt towers such as shown in US Patent Application 2008/0000231. These types of towers typically operate at temperatures up to about 600° C. Greater power generation efficiency could be achieved with operational temperatures in excess of 600° C. It is difficult to achieve operational temperatures above 600° C. with conventional CSP strategies.

[0004] Concentrating solar towers for driving chemical reactions have been suggested in several forms. One known concept uses concentrated sunlight to generate heat to decompose biomass, such as described in US Patent Application 2010/0249468. Another known method features the use of concentrated sunlight to cause water to undergo photolysis through interaction with catalysts, such as described in U.S. Pat. No. 4,045,315. Other technologies use concentrated sunlight and a reduction/oxidation cycle to create hydrogen gas from water or carbon monoxide gas from carbon dioxide, such as described in US Patent Application 2009/0107044. The foregoing chemical methods are not particularly well suited for the generation of electrical power using known power turbine based power cycles.

[0005] Maximizing the efficiency of a power plant for a concentrating solar power system is of great importance because it causes a reduction in overall system capital cost by requiring a smaller solar field and receiver for the same net energy production. In a concentrated solar power tower, the overall solar-to-electric efficiency is the product of the solar field efficiency, the receiver (solar-to-thermal) efficiency, the

storage efficiency, and the power cycle (thermal-to-electric) efficiency. The thermal-to-electric conversion system is very similar to fossil fuel systems at comparable temperatures, however, the conversion efficiency of a solar power cycle is typically much less than that of a combined cycle gas plant due to the lower operational temperatures.

[0006] The embodiments disclosed herein are directed toward overcoming one or more of the problems discussed above.

SUMMARY OF THE EMBODIMENTS

[0007] The embodiments disclosed herein include concentrating solar power (CSP) systems and methods which couple a thermal and a chemical energy pathway. The thermal pathway utilizes a heat transfer fluid to collect concentrated sunlight as thermal energy at medium temperature and transfer this energy to a thermal-to-electric power cycle. In parallel, the chemical pathway uses a redox material which undergoes direct photoreduction in the receiver to store the solar energy as chemical potential. This redox material is then oxidized at very high temperatures in the power cycle in series with the thermal pathway heat exchanger. This coupling allows the receiver to perform at the high efficiencies typical of state of the art thermal power towers while simultaneously achieving the power cycle efficiencies typical of natural gas combustion plants and achieving a very high overall solar-to-electric conversion efficiency.

[0008] One disclosed embodiment is a CSP system comprising a solar receiver configured to receive concentrated solar flux and a quantity of heat transfer fluid (HTF) in thermal communication with the solar receiver such that concentrated solar flux heats the HTF. The system also includes a heat exchanger in thermal communication with the HTF providing for heat exchange between the HTF and the working fluid of a power generation cycle. In addition, the system also includes a chemical energy storage material flowing in a chemical pathway coupled to the thermal pathway. The chemical energy storage material is also in communication with the solar receiver such that concentrated solar flux reduces a quantity of the chemical energy storage material in the reduction portion of an oxidation-reduction reaction. Thus, the chemical energy storage material can be alternatively referred to as a redox material.

[0009] The system further includes an oxidizer in communication with the chemical energy storage material, the oxidizer providing for the exothermic oxidation of the chemical energy storage material and further providing for heat exchange between the chemical energy storage material and the working fluid of the power cycle. Thus, the system utilizes parallel energy pathways, one thermal and one chemical. The use of two pathways coupled at the solar receiver results in a high-efficiency CSP plant.

[0010] The system may further include thermal energy storage operatively associated with a HTF conduit. In addition, the system may include separate chemical energy storage including a reduced chemical storage system operatively receiving reduced chemical energy storage material from the solar receiver; and/or an oxidized chemical storage system receiving oxidized chemical energy storage material from the oxidizer.

[0011] An alternative embodiment disclosed herein comprises a power generation method having certain steps which may be performed in any suitable order and which typically will be performed in a cyclical fashion. The method embodi-

ments are initiated by providing a solar receiver configured to receive concentrated solar flux. HTF of any suitable type is flowed, transported or otherwise brought into thermal communication with the solar receiver where the HTF is heated with the concentrated solar flux. The heated HTF is then flowed or transported from the solar receiver to a heat exchanger in a heat transfer fluid conduit. In the heat exchanger heat is exchanged between the heated heat transfer fluid and the working fluid of a power cycle.

[0012] In a parallel cycle, a chemical energy storage (redox) material in communication with the solar receiver is irradiated by the concentrated solar flux thereby causing a quantity of the chemical energy storage material to be reduced. The reduced chemical energy storage material is then flowed or transported between the solar receiver and an oxidizer element. In the oxidizer, the chemical energy storage material is oxidized causing the release of heat energy. The released heat energy is exchanged with the working fluid of the power cycle. Power may then be generated with the heated working fluid of the power cycle,

[0013] The disclosed embodiments all feature dual thermal and chemical energy pathways. The embodiments may be implemented in any type of concentrating solar power apparatus and with any type of power generation cycle or cycles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 is a simplified system schematic diagram illustrating a prior art CSP system.

[0015] FIG. 2 is a simplified system schematic diagram illustrating one embodiment of a system having thermal and chemical energy pathways as described herein.

[0016] FIG. 3 is a schematic diagram illustrating a redox cycle.

[0017] FIG. 4 is a simplified power cycle schematic illustrating a representative power cycle suitable for implementation with the systems disclosed herein.

[0018] FIG. 5 is simplified receiver schematics illustrating how the coupled pathways disclosed herein reduce radiative losses.

[0019] FIG. 6 is a simplified system schematic diagram illustrating an alternative received design.

[0020] FIG. 7 is a flow chart representation of a representative method as disclosed herein.

DETAILED DESCRIPTION

[0021] Unless otherwise indicated, all numbers expressing quantities of ingredients, dimensions reaction conditions and so forth used in the specification and claims are to be understood as being modified in all instances by the term “about”.

[0022] In this application and the claims, the use of the singular includes the plural unless specifically stated otherwise. In addition, use of “or” means “and/or” unless stated otherwise. Moreover, the use of the term “including”, as well as other forms, such as “includes” and “included”, is not limiting. Also, terms such as “element” or “component” encompass both elements and components comprising one unit and elements and components that comprise more than one unit unless specifically stated otherwise.

[0023] As noted above, known CSP systems generally operate at significantly less overall efficiency when compared to a combined cycle gas power generation plant. The reduced efficiency of a CSP system is primarily due to lower operational temperatures. To maximize overall solar plant effi-

ciency, it would be advantageous to use the high-efficiency power cycles available to combined cycle gas systems with a CSP plant, assuming this could be accomplished without compromising the balance of the CSP plant. This goal cannot be accomplished in state-of-the-art solar power towers, such as nitrate salt towers or superheated steam towers. In these towers, the energy pathway is strictly thermal, meaning that all the energy transferred from the receiver to the power cycle is transferred as thermal energy. A representative energy flow in a conventional CSP system is illustrated in FIG. 1. Solar radiation is concentrated by the solar field. The concentrated solar radiation is transferred as thermal energy to the receiver and captured with an intermediate heat transfer fluid. Thermal energy is then stored as hot stock heat transfer fluid in large tanks. When needed, the hot heat transfer fluid is sent to the power cycle via a heat exchanger. Finally, thermal energy is converted into electricity in a thermodynamic power cycle.

[0024] In known CSP plant configurations, the factors driving the receiver and power cycle efficiencies are fundamentally counteracting one another. The efficiency of the power cycle increases with the inlet temperature of the heat transfer fluid. However, the efficiency of the solar receiver goes down with increasing temperature due to higher convective and radiative heat losses. In addition, the receiver has absolute temperature limits because of salt decomposition and receiver material constraints. Because the power cycle and receiver temperatures are fundamentally coupled in a plant with only a thermal energy pathway, very high overall system efficiencies cannot be achieved.

[0025] The system and method embodiments disclosed herein utilize parallel energy pathways, one thermal and one chemical in a high-efficiency concentrated solar power (CSP) plant. As shown in FIG. 2, a representative system 100 includes one or more thermal pathways 102 consisting of a heat transfer fluid (HTF) such as steam/water, molten or solid salt, molten or solid metal, oil a phase change material or other suitable HTF in thermal communication with a solar receiver 104. The solar receiver 104 is typically associated with a central receiver tower and receives concentrated solar flux reflected by a field of heliostats. The methods disclosed herein could be implemented with other CSP designs however, including but not limited to parabolic trough, linear Fresnel, and dish/engine systems.

[0026] HTF heated at the solar receiver 104 is flowed or transported to a heat exchanger 106 in a heat transfer fluid conduit 108. It is important to note that although the conventional terminology of heat transfer fluid (HTF) is used herein, the system and methods may be implemented with a liquid, solid, gaseous or phase-changing HTF. Thus, the heat transfer fluid conduit 108 may be a system of pipes or ducts and valves suitable for the control of fluid flow, or the heat transfer fluid conduit 108 may be any type of system suitable for transporting solids. The heat transfer fluid conduit 108 may include some fluid flow sections and some solid transport sections.

[0027] In the heat exchanger 106, thermal energy is exchanged between the HTF and the working fluid of a power cycle. The heat exchanger(s) may be of any type or any level of sophistication needed to provide for heat exchange between the HTF and a power generation cycle working fluid. The heat exchanger 106 and other subsystems are, for technical convenience, described and shown in the figures as simple schematic elements. All elements of a commercial system would be implemented with more complex apparatus. As generally shown in FIG. 2, the heated working fluid drives

a power generation cycle **110**. Accordingly, the working fluid is, either directly or through an intermediate power cycle fluid, converted to mechanical energy and then electrical energy.

[0028] The system **100** and methods disclosed herein also include a parallel chemical energy pathway which includes a chemical energy storage material which undergoes reversible reduction and oxidation reactions (alternatively referred to herein as a “redox material”). In particular, the redox material is reduced in the receiver **104** and oxidized in an oxidizer **112**. The oxidizer or an associated apparatus also provides for heat exchange with the working fluid of the power cycle **110**. The redox material is flowed or transported between the receiver and oxidizer in a chemical energy storage material conduit **114** which may be configured for fluid flow or solid transport as described above with respect to the HTF conduit **108**.

[0029] As noted above, the redox material is directly photoreduced by the high concentration of incident photons in the receiver **104**, thus, the redox material stores the absorbed electromagnetic energy as a chemical potential. In the oxidizer **112**, the redox material is oxidized, thereby releasing high temperature thermal energy. A representative diagram of this type of chemical process is shown in FIG. **3** and described below. It is important to note that the oxidizer element **112** will typically be implemented with apparatus of significantly more complexity than is shown on FIG. **2**. For example, the oxidizer **112** may include separate oxidation chambers, air or gas supplies, fluidized bed, heat exchanger and other elements.

[0030] Typically, CSP systems achieve a certain level of efficiency when implemented, for example, with current state of the art steam or molten salt receivers. In addition, power plants implemented with combustive power cycles have very good performance (for example, combined cycle natural gas plants). The coupled thermal-chemical architecture described herein allows a CSP system to take advantage of both power generation technologies without any fossil fuel consumption or environmentally harmful emissions. Thus, the disclosed systems and methods have an advantage over known state-of-the-art CSP plants in increased thermal-to-electric conversion efficiency due in part to the high temperature of the oxidation process. For example, typical steam or molten salt CSP based power generation plants achieve thermal-to-electric efficiencies of 40-44%. As shown in FIG. **2** and detailed below, the disclosed systems and methods can achieve temperatures suitable to drive a power generation system having overall efficiencies of approximately 60% which are much closer to the efficiencies exhibited by combined cycle natural gas plants

[0031] The chemical energy pathway described above represents new system architecture in the CSP industry. Whereas a thermal pathway transfers energy by heating and cooling a heat transfer fluid, a chemical pathway transfers energy by storing energy in a material via an endothermic reaction and releasing it in an exothermic reaction. As noted above, the chemical pathway will consist of a material undergoing reversible reduction and oxidation reactions. For illustration purposes, one potential set of reactions is shown in FIG. **3**, although the embodiments disclosed herein can be implemented with many alternative redox materials.

[0032] As schematically illustrated in FIG. **3**, a representative redox cycle features a reduction step (top box) which takes place in the solar receiver. A photon hits the oxidized material and breaks it into a reduced material and free oxy-

gen. This step depends only on the photon directly supplying energy to break the bond between the metal and oxygen atoms. The reduced material (MnO in this example) is transferred to a storage tank. When it is needed, it is transferred to the power cycle where it is burned in oxygen releasing heat and closing the loop by recreating the original oxidized material.

[0033] The foregoing representative redox process is governed by the balance between the energy of the chemical bonds and the energy of the photon. The bond energies are typically described in terms of Gibbs free energy, ΔG , and the energy required to drive an endothermic reaction or the energy released by an exothermic reaction can be calculated with Equation 1.

$$\Delta G_{\text{reaction}} = \sum \text{coeff}_{\text{products}} \Delta G_{\text{products}} - \sum \text{coeff}_{\text{reactants}} \Delta G_{\text{reactants}} \quad \text{Equation 1}$$

[0034] Reference ΔG values can be obtained from chemistry texts, NIST databases, or other sources. The coefficients come from the balanced chemical equation. For direct photoreduction to occur, the energy of the photon causing the reaction must be higher than the free energy required to drive the reaction. To compare the energies, the photon energy can be calculated from Equation 2.

$$E_{\text{photon}} = \frac{hc}{\lambda} \quad \text{Equation 2}$$

[0035] where h is Planck’s constant, c is the speed of light, and λ is the photon’s wavelength. Photons available for solar collection are generally in the visible range, 380-750 nm.

[0036] Several potential redox materials have been examined for suitability in the described systems using Equations 1 and 2. A sample of the results is presented in Table 1. All calculations presented assume a reaction temperature of 500° C.

TABLE 1

Sample of calculations for redox material direct photoreduction		
Balanced chemical equation	$\Delta G_{\text{reaction}}$ [kJ/mol _{reactant}]	Required photon wavelength
$\text{Mn}_2\text{O}_3 + h\nu \rightarrow 2\text{MnO} + \frac{1}{2}\text{O}_2$	30	<3940 nm
$2\text{Al}_2\text{O}_3 + h\nu \rightarrow 4\text{Al} + 3\text{O}_2$	717	<167 nm
$\text{CoO} + h\nu \rightarrow \text{Co} + \frac{1}{2}\text{O}_2$	176	<678 nm
$\text{NiO} + h\nu \rightarrow \text{Ni} + \frac{1}{2}\text{O}_2$	167	<718 nm

[0037] From this table, it can be seen that aluminum is not a good redox material option because its oxide cannot be reduced by visible light. Cobalt and nickel oxides cannot absorb from the entire red end of the spectrum but could capture most of the available energy.

[0038] Manganese oxide, alternatively, does not absorb the full energy of visible light for the reaction so some of the photon energy will be converted to kinetic or thermal energy instead.

[0039] An ideal chemical energy storage (redox) material for the described system will have four characteristics:

[0040] A high absorptivity in the UV and visible spectrum so the maximum amount of light is absorbed.

[0041] An energy difference between the oxidized and reduced states slightly smaller than the energy of visible

spectrum photons so the greatest amount of energy will be converted from electromagnetic to chemical potential.

[0042] A low oxidation rate at lower temperatures and in the absence of an ignition mechanism to minimize re-oxidation before the desired time.

[0043] A high oxidation rate at the conditions of the power cycle to maximize efficiency.

[0044] Several materials exhibiting these characteristics to varying degrees have been previously identified. Generally, the best known materials are transition metal oxides. For example, manganese oxides and cobalt oxides with additions of iron oxide and aluminum oxide have previously been identified as prime candidates for direct photoreduction technologies. See, for example, General Atomics. “*Thermochemical heat storage for concentrated solar power based on multivalent metal oxides*.” DOE Program Review, May 2011. http://www1.eere.energy.gov/solar/csp_pr2011.html accessed on Dec. 19, 2011, which disclosure is incorporated herein in its entirety. However, heat loss management was identified as a problem in the above rotary kiln reactor study. Additionally, the fraction of material undergoing reduction was low, on the order of 3%, leading to high capital costs.

[0045] The systems and methods disclosed herein use solar photons to directly photoreduce the redox material. The energy does not go through a thermal state in between the electromagnetic (solar photon) and the chemical potential state. In fact, the disclosed technology works best with materials that do not thermochemically dissociate below 1400° C., the desired power cycle hot temperature, which is much hotter than achievable with known CSP technologies.

[0046] The system and methods disclosed herein can be utilized to drive any type of power generation cycles. The known power cycle most suited to operation at efficiencies near or above 60% is however, an air-Brayton cycle or a variation thereof. A highly simplified diagram of one possible representative and non-limiting power cycle layout 400 is illustrated in FIG. 4. The FIG. 4 example layout illustrates how the thermal and chemical heat sources described above could be integrated into an air-Brayton power cycle 402 in conjunction with a steam Rankine bottoming cycle 404. As noted above, other power cycles could also be used. Certain advantages can be realized if the working fluid contains an oxidizing agent. For example, an open-loop supercritical carbon dioxide or steam cycle could be used where the CO₂ or H₂O would be reduced to CO or H₂, respectively, which could then be used for liquid fuel generation or as fuel for fuel cells.

[0047] In the FIG. 4 embodiment, the upper open air Brayton cycle utilizes air as a working fluid and oxidizing agent. The air is initially compressed in compressor 406 which is driven by a mechanical connection to a downstream turbine 408. The compressed air from the compressor 406 is heated through heat exchange with the HTF in heat exchanger 106. The heated and compressed air oxidizes the chemical energy storage material in the oxidizer 112 and thus is further heated by direct contact or indirect heat exchange with the chemical energy storage material as it releases heat during the exothermic oxidation reaction. The now high temperature air drives one or more turbines 408 which in turn drive the compressor 406 and one or more generators (not shown on FIG. 4) to generate electrical energy.

[0048] The FIG. 4 embodiment also includes a lower steam Rankine bottoming cycle 404 receiving somewhat cooled air from the outlet of the turbine 408. Heat is exchanged between

the air and a secondary working fluid, for example steam, in a recuperator/heat exchanger 410. The heated steam then drives a second turbine 412 or a second series of turbines which in turn drive one or more generators to generate electrical energy. Steam exiting the turbine 412 is condensed in a condenser 414 and pumped as water back to the recuperator/heat exchanger 410 by pump 416.

[0049] One source of inefficiency for thermochemical and direct photoreduction chemical receivers is heat loss during the reduction stages. In a coupled thermal-chemical receiver as described herein, some or most of the heat losses from the redox material can be recaptured by the thermal receiver and any residual heat stored in the redox material at the outlet of the receiver can be transferred back to pre-heat the cool HTF entering the receiver.

[0050] A diagram illustrating a receiver design with improved heat loss management is shown in FIG. 5. Incident solar radiation (shown as arrows 502) is concentrated on the receiver 104 where some of the photons are absorbed by the redox material (dots 504). A large part of the remaining incident photons are absorbed by the thermal receiver (illustrated as panel 506). HTF is flowing within the panel 506 absorbing heat. Of the photons absorbed by the redox material, some cause photoreduction while others directly heat the redox material. Some of this absorbed heat is radiated and lost to the environment but some is reabsorbed by the thermal receiver (illustrated by the dashed arrows 508). Similarly, some of the radiation losses from the thermal receiver will be reabsorbed by the redox material. Because the redox material will be at a lower temperature than the thermal receiver, the average surface temperature seen by the environment will be lower than the thermal receiver surface temperature, thereby reducing total radiative thermal losses. Therefore, despite the relatively lower efficiency of the photoreduction step, the receiver will still maintain high total efficiency.

[0051] The receiver embodiment of FIG. 5 couples a gravity fed curtain of redox material with a traditional cavity receiver tube sheet having HTF cooling. Alternatively, as shown in FIG. 6, the receiver element may be implemented as a rotating cavity receiver 104 in which the walls are cooled by HTF and baffles are used to continuously drop the redox material 600 through the cavity space. In the FIG. 6 configuration, the redox material particles are contained in one or more rotating cavity receivers 602. As the receiver 602 rotates, the particles 600 are agitated and fall through the space, absorbing solar radiation. Some of the photons will be absorbed by the reactor walls instead of the particles and will be converted to heat. The reactor walls will be cooled by the thermal pathway's heat transfer fluid 604. This configuration provides for minimized radiative and convective heat losses and maximizes the conversion of solar energy to thermal energy and chemical potential.

[0052] A further advantage of the coupled thermal-chemical pathway system is that the parallel thermal and chemical systems can be used to store energy over different time scales. Thermal CSP systems, such as molten salt towers, provide for relatively low cost short term (day scale) thermal energy storage. For example, referring to FIG. 2, heated HTF may be stored directly in a hot thermal storage system 116 operatively associated with the HTF conduit 108 receiving flow from the receiver 104 before the heat exchanger 106. Alternatively, heated HTF could be used to heat a separate thermal storage medium through heat exchange at the hot thermal storage system. Heat may then be provided to the HTF from

the hot thermal storage system **116** during periods of low solar flux, in the evening or during periods of cloud cover for example. Similarly, cooled HTF may be stored, or used to heat a separate heat storage medium in a cold thermal energy storage system **118**. The cold thermal energy storage system **118** could be operatively associated with the HTF conduit **108** to receive flow from the heat exchanger **106** to the receiver **104** and used as above during periods of lower solar radiation.

[0053] The disclosed parallel chemical system enables longer term (seasonal) storage because the redox material is not stored at a high temperature and therefore does not suffer from heat losses during storage. For example, as also shown in FIG. 2, oxidized or reduced redox material can be stored for an extended period of time in an oxidized chemical storage material storage system **120** and reduced chemical storage material storage system **122** respectively. Both chemical storage systems **120** and **122** could be operatively associated with the chemical energy storage material conduit with the oxidized material storage system being downstream from the oxidizer **112** and the reduced material storage system being downstream from the receiver **104**.

[0054] One representative embodiment of the system **100** uses an aluminum silicon (AlSi) phase change material (PCM) as the HTF or in this example, the heat transfer material. AlSi PCM can reach higher temperatures than steam or nitrate salts thereby providing improved receiver performance. Higher temperatures are advantageous because the system will perform best when the majority of the system heat requirement is supplied by a high efficiency thermal receiver.

[0055] As noted above, the disclosed system and methods may advantageously be implemented in a power tower configuration consisting of a heliostat field focused on a receiver on top of a tower structure. The AlSi PCM (or other suitable HTF) and the redox material will be transferred from the receiver to storage vessels or storage systems at the base of the tower. The PCM or other suitable HTF and redox materials may then be transferred to the power cycle as needed for electricity generation.

[0056] As noted above, one suitable but non-exclusive thermal-to-electric conversion system is an open air-Brayton power cycle with a steam Rankine bottoming cycle. The inlet air will be compressed to high pressure, passed through a heat exchanger with the AlSi PCM or other HTF to heat it to medium temperatures, then passed through the oxidation chamber to oxidize the redox material and heat the air the very high temperatures. The highly heated air will be used to power a turbine and electric generator. The exhaust air will be used as the heat source for a typical steam bottoming Rankine cycle via a heat recovery steam generator.

[0057] The disclosed embodiments also include power generation methods, for example the power generation method **700** illustrated in FIG. 7. The FIG. 7 method includes several steps which may be performed in any suitable order and which typically will be performed in a cyclical fashion. The method is initiated by providing a solar receiver configured to receive concentrated solar flux (step **702**). Heat transfer fluid of any type is flowed, transported or otherwise brought into in thermal communication with the solar receiver where the HTF is heated with the concentrated solar flux (step **704**). The heated HTF is then flowed or transported from the solar receiver to a heat exchanger in a heat transfer fluid conduit (Step **706**). In the heat exchanger heat is exchanged between the heated heat transfer fluid and the working fluid of a power cycle (Step **708**).

[0058] In a parallel cycle, a chemical energy storage (redox) material in communication with the solar receiver is irradiated by the concentrated solar flux thereby causing a quantity of the chemical energy storage material to be reduced (Step **710**). The reduced chemical energy storage material is then flowed or transported between the solar receiver and an oxidizer in a chemical energy storage material conduit (Step **712**). In the oxidizer, the chemical energy storage material is oxidized causing the release of heat energy (Step **714**). The released heat energy is exchanged with the working fluid of the power cycle (Step **716**). Power may then be generated with the heated working fluid of the power cycle (Step **718**).

[0059] In summary, the systems and methods described herein featuring coupled thermal and chemical pathways will potentially achieve a higher overall solar-to-electric conversion rate than any other known CSP technology. This will translate to direct capital cost and LCOE savings because each component can be proportionally smaller for a selected rate of electricity generation. A comparison of the disclosed technology to the state of the art and developing CSP technologies can be found in Table 2. All values in this table are estimates of target values and many have not been proven commercially to date.

TABLE 2

Comparison of proposed technology to state of the art and developing technologies (estimated target values)					
	Solar field efficiency	Receiver efficiency	Storage efficiency	Power Cycle efficiency	Overall Efficiency
Molten salt	50-60%	80-90%	97%	40-45%	16-24%
Air	50-60%	70-80%	n/a	50-55%	18-26%
Saturated Steam	50-60%	85-90%	n/a	30-35%	13-19%
Superheated Steam	50-60%	80-85%	n/a	40-45%	16-23%
Solid particle	50-60%	60-70%	97%	45-50%	13-20%
Coupled thermal and chemical	50-60%	70-85%	97%	55-60%	19-30%

[0060] In addition to high system efficiency at low cost, the coupled chemical-thermal pathway systems and methods offer two other significant benefits. First, as described in detail above, the two energy pathways offer two means of energy storage. The thermal pathway can utilize any existing thermal storage system for short term storage. This is an important advantage that CSP holds over wind and photovoltaic technologies because it allows CSP plants to match demand while reducing the LCOE. The described system can also couple inexpensive short term storage with long term chemical storage to match seasonal demand. Once reduced, the redox material can be stored in an inert environment for very long periods of time and used for power production as needed. This will further allow CSP to meet grid demands during times when very little renewable generation is available.

[0061] The second additional benefit is the ability to produce syngas. Instead of using air as the oxidant in power cycle, the redox material could be combusted with carbon dioxide or steam to produce carbon monoxide or hydrogen. Together, these two gases constitute syngas which can be used to create liquid fuels. This process would possibly

decrease the electric generation capacity of the system but may be a relatively efficient way to produce renewable carbon-neutral fuels.

[0062] Various embodiments of the disclosure could also include permutations of the various elements recited in the claims as if each dependent claim was a multiple dependent claim incorporating the limitations of each of the preceding dependent claims as well as the independent claims. Such permutations are expressly within the scope of this disclosure.

[0063] While the invention has been particularly shown and described with reference to a number of embodiments, it would be understood by those skilled in the art that changes in the form and details may be made to the various embodiments disclosed herein without departing from the spirit and scope of the invention and that the various embodiments disclosed herein are not intended to act as limitations on the scope of the claims. All references cited herein are incorporated in their entirety by reference.

What is claimed is:

1. A concentrating solar power system comprising:
 - a solar receiver configured to receive concentrated solar flux;
 - heat transfer fluid in thermal communication with the solar receiver such that concentrated solar flux heats a quantity of the heat transfer fluid;
 - a heat exchanger in thermal communication with the heat transfer fluid, the heat exchanger providing for heat exchange between the heat transfer fluid and a working fluid of a power cycle;
 - a heat transfer fluid conduit providing for the flow or transport of heat transfer fluid between the solar receiver and the heat exchanger;
 - chemical energy storage material in communication with the solar receiver such that concentrated solar flux reduces a quantity of the chemical energy storage material;
 - an oxidizer in communication with the chemical energy storage material, the oxidizer providing for the oxidation of the chemical energy storage material and further providing for heat exchange between the chemical energy storage material and the working fluid of the power cycle; and
 - a chemical energy storage material conduit providing for the flow or transport of chemical energy storage material between the solar receiver and the oxidizer.
2. The concentrating solar power system of claim 1 further comprising a thermal energy storage system operatively associated with the heat transfer fluid conduit.
3. The concentrating solar power system of claim 2 further comprising:
 - a hot thermal energy storage system receiving heated heat transfer fluid from the solar receiver; and
 - a cold thermal energy storage system receiving cooled heat transfer fluid from the heat exchanger.
4. The concentrating solar power system of claim 1 further comprising:
 - a reduced chemical energy storage material storage system operatively associated with the chemical energy storage material conduit and receiving reduced chemical energy storage material from the solar receiver; and
 - an oxidized chemical energy storage material storage system operatively associated with the chemical energy

storage material conduit and receiving oxidized chemical energy storage material from the oxidizer.

5. The concentrating solar power system of claim 1 wherein the heat transfer fluid comprises one or more of water, a solid salt; a molten salt, a solid metal; a molten metal and an oil.

6. The concentrating solar power system of claim 1 wherein the heat transfer fluid comprises an aluminum silicon phase change material.

7. The concentrating solar power system of claim 1 further comprising:

- a tower supporting the solar receiver; and
- a heliostat field having heliostats positioned to focus sunlight on the receiver.

8. The concentrating solar power system of claim 1 wherein the power cycle comprises:

- an open air Brayton upper power cycle; and
- steam Rankine bottoming cycle.

9. The concentrating solar power system of claim 1 wherein the working fluid of the power cycle contains an oxidizing agent.

10. A power generation method comprising:

- providing a solar receiver configured to receive concentrated solar flux;
- heating a heat transfer fluid in thermal communication with the solar receiver with the concentrated solar flux;
- flowing or transporting the heat transfer fluid between the solar receiver and a heat exchanger in a heat transfer fluid conduit;
- exchanging heat between the heated heat transfer fluid and a working fluid of a power cycle within the heat exchanger;
- reducing a chemical energy storage material in communication with the solar receiver by irradiating the chemical energy storage material with concentrated solar flux;
- flowing or transporting the reduced chemical energy storage material between the solar receiver and an oxidizer in a chemical energy storage material conduit;
- oxidizing the reduced chemical energy storage material in an oxidizer, the oxidizer further providing for heat exchange between the chemical energy storage material and the working fluid of the power cycle; and
- generating power with the working fluid of the power cycle.

11. The method of claim 11 further comprising storing heat transfer fluid in a thermal energy storage system operatively associated with the heat transfer fluid conduit.

12. The method of claim 11 further comprising:

- storing heated heat transfer fluid received from the solar receiver in a hot thermal energy storage system; and
- storing cooled heat transfer fluid received from the heat exchanger in a cold thermal energy storage system.

13. The method of claim 11 further comprising:

- storing reduced chemical energy storage material received from the receiver in a reduced chemical energy storage material storage system; and
- storing oxidized chemical energy storage material received from the oxidizer in an oxidized chemical energy storage material storage system.

14. The method of claim 11 wherein the heat transfer fluid comprises one or more of water, a solid salt; a molten salt, a solid metal; a molten metal and an oil.

15. The method of claim 11 wherein the heat transfer fluid comprises an aluminum silicon phase change material.

16. The method of claim **11** further comprising:
providing a tower to support the solar receiver; and
providing a heliostat field having heliostats positioned to
focus sunlight on the receiver.

17. The method of claim **11** further comprising generating
power with a power cycle comprising:
an open air Brayton upper power cycle; and
steam Rankine bottoming cycle.

18. The method of claim **11** further comprising oxidizing
the reduced chemical energy storage material in the oxidizer
with a oxidizing agent in the working fluid of the power cycle.

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