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Hybrid metal oxide cycle water splitting

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(54) **HYBRID METAL OXIDE CYCLE WATER SPLITTING**

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CPC C25B 1/00; C25B 1/04; C25B 9/00; C25B 9/06; C25B 15/08; H01M 8/0656

See application file for complete search history.

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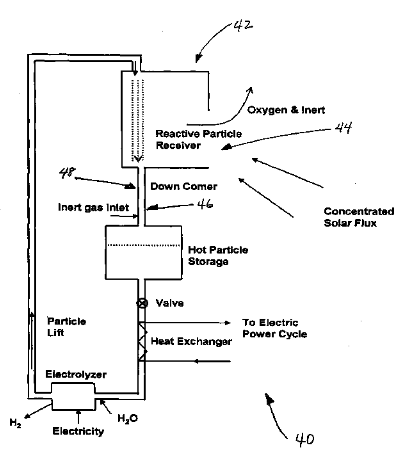
(57) **ABSTRACT**

Hybrid thermochemical water splitting systems are disclosed that thermally reduces metal oxides particles to displace some but not all of the electrical requirements in a water splitting electrolytic cell. In these hybrid systems, the thermal reduction temperature is significantly reduced compared to two-step metal-oxide thermochemical cycles in which only thermal energy is required to produce hydrogen from water. Also, unlike conventional higher temperature systems where the reduction step must be carried out under reduced oxygen pressure, the reduction step in the proposed hybrid systems can be carried out in air, allowing for thermal input by a solar power tower with a windowless, cavity receiver.

9 Claims, 2 Drawing Sheets



Related U.S. Application Data

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(51) **Int. Cl.**

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C25B 9/06	(2006.01)
C25B 15/08	(2006.01)
H01M 8/06	(2016.01)
C01B 3/06	(2006.01)

(52) **U.S. Cl.**

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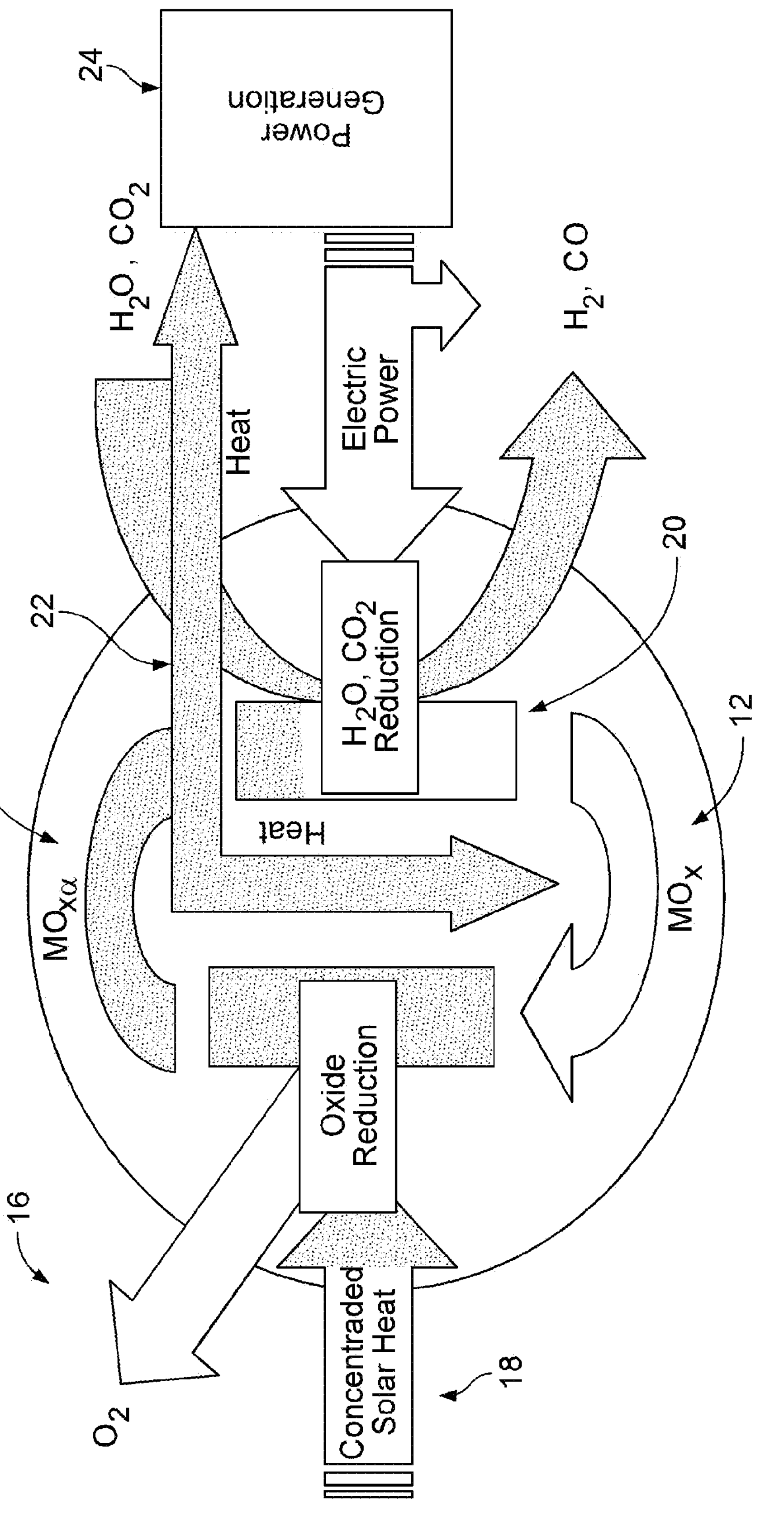
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Power Generation
H_2O, CO_2
Heat
Electric Power
H_2, CO
22
20
H_2O, CO_2 Reduction
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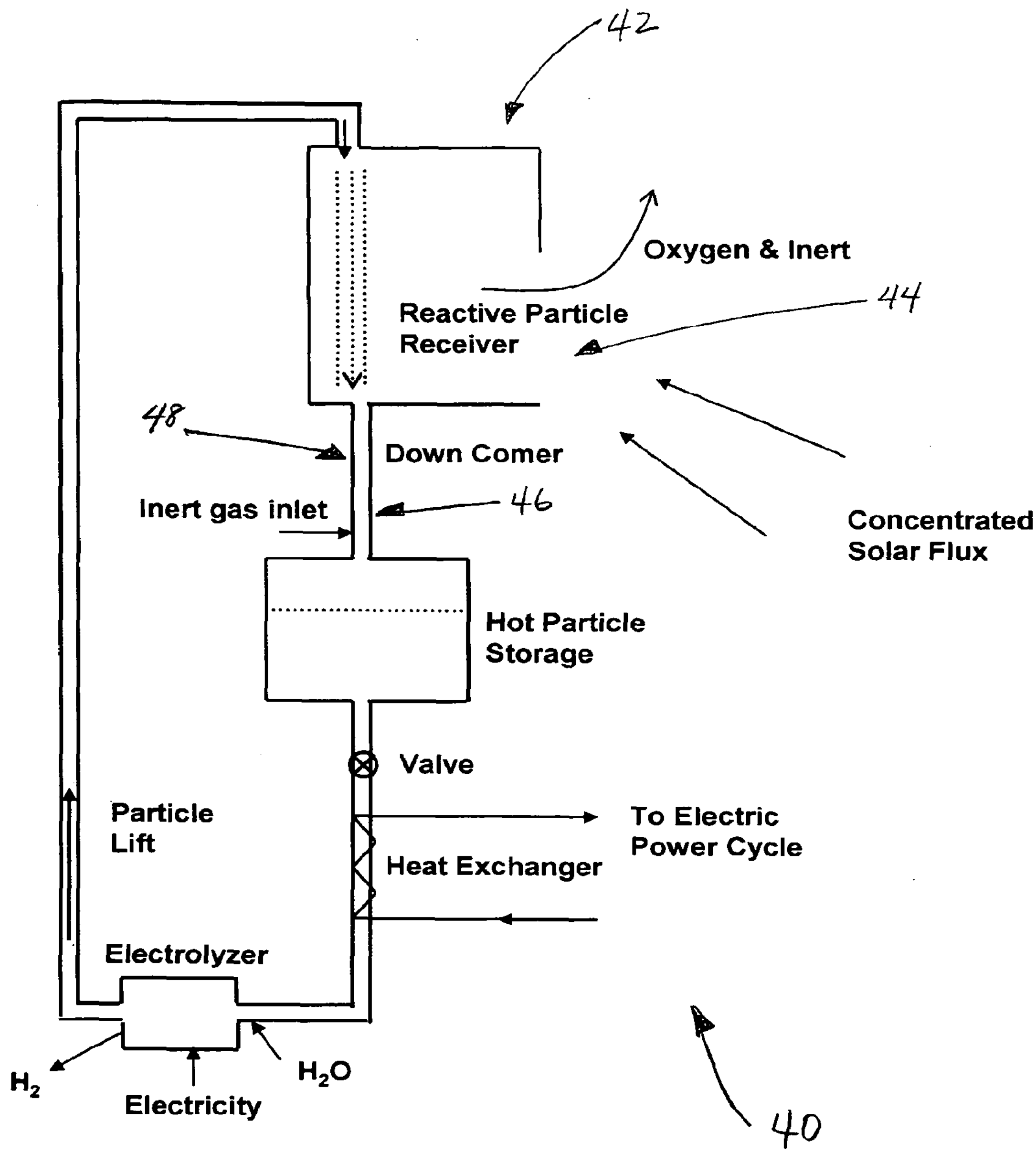
Heat
MO_x
Oxide Reduction
16
O_2
Concentraded Solar Heat
18

Figure 1

10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44
Reactive Particle
Receiver
48
Down Comer
Inert gas inlet
46
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Solar Flux
Hot Particle
Storage
Valve
Particle
Lift
To Electric
Power Cycle
Heat Exchanger
Electrolyzer
H2
Electricity
H2O
40

FIG. 2

HYBRID METAL OXIDE CYCLE WATER SPLITTING

CROSS REFERENCE TO RELATED APPLICATION

This application is a divisional of U.S. application Ser. No. 14/115,095, entitled "HYBRID METAL OXIDE CYCLE WATER SPLITTING," filed on Oct. 31, 2013, which is a 35 U.S.C. 371 national stage application of PCT International Application No. PCT/US2011/001340 filed Jul. 29, 2011, which claims priority to U.S. Provisional Application Ser. No. 61/368,756, filed on Jul. 29, 2010, all of which are hereby incorporated by reference in their entireties.

BACKGROUND OF THE DISCLOSURE

The present disclosure relates generally to methods and apparatus associated with hybrid metal oxide cycle water splitting.

SUMMARY OF THE INVENTION

In one aspect of the disclosure, a hybrid thermochemical splitting cycle implementation is disclosed that includes a reactive particle receiver including an open cavity, a down comer, a hot particle storage container, a heat exchanger, and an electrolyzer. The oxidized particles are directly heated and thermally reduced in the open cavity. Within the hybrid thermochemical splitting cycle implementation, a hybrid thermochemical splitting cycle is performed that includes thermally reducing a metal oxide with concentrated solar energy and reoxidizing an oxygen-deficient metal oxide in an electrochemical cell, wherein the chemical potential for the reactions is provided by the metal oxide and electrical energy, and wherein the electrical energy required is significantly lower than needed for water or carbon dioxide electrolysis alone.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a schematic view of a hybrid metal oxide cycle; and

FIG. **2** shows one implementation strategy of the hybrid metal oxide cycle of FIG. **1**.

DETAILED DESCRIPTION

Hybrid thermochemical water splitting cycles are proposed in which thermally reduced metal oxides particles are used to displace some but not all of the electrical requirements in a water splitting electrolytic cell. In these hybrid cycles, the thermal reduction temperature is significantly reduced compared to two-step metal-oxide thermochemical cycles in which only thermal energy is required to produce hydrogen from water. Also, unlike the conventional higher temperature cycles where the reduction step must be carried out under reduced oxygen pressure, the reduction step in the proposed hybrid cycles can be (but are not required to be) carried out in air, allowing for thermal input by a solar power tower with a windowless, cavity receiver. These proposed hybrid cycles could also potentially enable the use of heat from a nuclear reactor. Regardless of the energy input source, solar or nuclear, in the hybrid scheme the products from thermal reduction are utilized as a chemically active anode material in a water splitting electrolyzer. Because the anode is re-oxidized during electrolysis, the electrical input required to split water is reduced substantially below the electric input required to drive a conventional water splitting electrolyzer. For example, the ideal decomposition voltage can drop from the 1.23 volts needed in a conventional cell to values as low as 0.23 volts. This approach appears well suited to an electrolyzer where the anode is a packed or moving (possibly fluidized) bed of particles. The bed could either be stand-alone, or could be a mixture of a conductor, e.g. Ni metal, and the solar reduced oxide. This cell design concept could be integrated with a reactive-particle solid particle receiver. Appropriate sizing of the receiver relative to the electrolyzer would allow for round-the-clock continuous operation of the electrolyzer.

Thermochemical cycles are an attractive alternative to electrolysis as they have the potential for higher energy efficiency due to the fact that they avoid the need to first convert thermal energy into electrical energy. There are many proposed metal oxide thermochemical cycles for water splitting. For example, the Iron Oxide cycle is one that has been interesting to the research community because the reduced iron oxide is capable of reacting with water to produce hydrogen. However, in this cycle very high temperatures are needed to thermally reduce magnetite, Fe_3O_4, to the reduced oxide, wustite, FeO. Complicating matters is the fact that the recovery of FeO is dependent on the reduction step being conducted under reduced oxygen partial pressure, e.g. in a vacuum or in the presence of an inert sweep gas. Also, the oxides melt and are somewhat volatile at the required temperatures. The thermodynamic high temperature requirements and thermodynamic and kinetic requirements forcing the reaction to take place under an inert atmosphere as well as numerous materials challenges posed for these types of cycles compromise significantly the potential of engineering these cycles into an efficient and industrially economically realizable process. We are, therefore, interested in processes where the thermal reduction step can be done at temperatures below 1500° C. and even in air.

As an example, oxygen can be driven off from cobalt and manganese oxides (i.e. Co_3O_4 MnO_2, and Mn_2O_3) at significantly lower temperatures than needed to thermally reduce magnetite. In addition, oxygen can also be produced from hematite, Fe_2O_3, at much lower temperatures.

$$3Fe_2O_3 \rightarrow 2Fe_3O_4 + \tfrac{1}{2}O_2 \quad (1)$$

The factor previously eliminating the use of these attractive thermal reduction chemistries has been the other half of the two-step cycle. The Gibbs free energy, ΔG, of the oxidation Fe_3O_4 and the thermally reduced states of cobalt and manganese oxides with water are positive at any temperature above and including room temperature. That is, they are thermodynamically stable in the presence of water and steam, and will not spontaneously oxidize to yield hydrogen. (Note: Because the reaction with water is not favorable, steam is essentially inert in the system and could be employed gainfully as a sweep to promote the reduction reaction if desired).

The factor previously eliminating the use of these attractive thermal reduction chemistries has been the other half of the two-step cycle. The Gibbs free energy, ΔG, of the oxidation Fe_3O_4 and the thermally reduced states of cobalt and manganese oxides with water are positive at any temperature above and including room temperature. That is, they are thermodynamically stable in the presence of water and steam, and will not spontaneously oxidize to yield hydrogen. (Note: Because the reaction with water is not

favorable, steam is essentially inert in the system and could be employed gainfully as a sweep to promote the reduction reaction if desired).

$$2Fe_3O_4+H_2O(g)\rightarrow 3Fe_2O_3+H_2(g)\ \Delta G>0 \quad (2)$$

Employing a third reaction with sodium hydroxide or potassium hydroxide has been proposed to make the oxidation thermodynamics favorable for metal oxide cycles in which the oxidation reaction is not favorable However, the addition of the third reaction step and the addition of hydroxides significantly complicate the cycles. A key insight is that these oxidation reactions can be made favorable and the complications of a third step eliminated with the addition of only a small applied voltage at ambient temperature, one significantly less than that required for conventional electrolysis.

$$2Fe_3O_4+H_2O(g)+\text{Power (IV)}\rightarrow 3Fe_2O_3+H_2(g)\ \Delta G<0 \quad (3)$$

Comparison to Alternate Approaches:

The proposed hybrid cycle **10**, shown schematically in FIG. **1**, is similar to conventional two-step thermochemical cycles with the exception that the oxidation step is electrochemically assisted. In the hybrid thermochemical cycle **10**, a metal oxide **12** is thermally reduced (driving off oxygen **16**) with concentrated solar energy **18**. The oxygen deficient metal oxide **14** is subsequently reoxidized in an electrochemical cell **20** to reduce water to hydrogen or carbon dioxide to carbon monoxide. Heat **20** extracted from the reduced metal oxide **14** can be used for power generation **22**. The chemical potential for the water or carbon dioxide reducing reactions is provided by the reduced metal oxide and electrical energy. The electrical energy is required is significantly lower than needed for water or carbon dioxide electrolysis alone. The payoff for this hybrid approach is that the extreme challenges posed by the ultra-high temperature reduction (e.g. materials degradation, volatilization, limited heat source options, thermal energy management, closed systems with inert gas sweeps, etc.) are exchanged for a simpler electrochemical step. Because the hybrid cycle **10** is significantly more straight forward, it should be much easier to implement and thus in practice should be more efficient than the proposed processes that split water with an exothermic reaction like that corresponding the iron oxide cycle.

Note that in the hybrid approach, the reduction and oxidation steps of two step metal oxide cycles are separated and can be performed independently of each other. An advantage of this is that while the solar driven thermochemical step can be carried out when the sun is available, the electrochemically driven oxidation step can occur when convenient. Therefore, by over-sizing the thermally driven reduction process relative to the electrochemical oxidation process, it is possible to achieve round-the-clock operation. This has the benefit of maximizing the utilization of the electrochemical equipment and minimizing issues associated with starting and stopping the electrochemical reactor.

It may be noted that this metal-oxide hybrid approach is analogous to the Hybrid Sulfur cycle where the hydrogen production step is electrochemical vs. the 3-step Sulfur-Iodine thermochemical cycle. However, the metal oxide approach utilizes no corrosive or hazardous chemicals and utilizes only gas-solid and gas-liquid reactions, making for convenient separations of valuable products from the working materials. It is also worth pointing out that the hybrid process is an alternative to solar thermal electrolysis processes that have been explored over the past thirty years. They were motivated by the fact that the higher the operating temperature of an electrolytic cell the more one could substitute sunlight for valuable electric work. Thus a number of studies show running modestly high solar processes where sunlight and electric energy is simultaneously supplied to the solar reactor. Our hybrid metal oxide cycle **10** is thermodynamically equivalent to this approach, but by separating the electrolytic step from the thermal reduction step, one greatly reduces the complexity of the solar reactor and allows for a quasi-24-hour continuous solar process. The thermodynamics of metal oxide cycles allow for a much higher percentage of thermal vs. electrical contribution to water splitting at lower temperatures, compared to direct high-temperature water electrolysis.

Materials and Thermodynamics:

A non-exclusive list of metal oxides we believe are of interest for this hybrid approach includes Fe_2O_3, MnO_2, Mn_2O_3, and Co_3O_4 where the products from the solar reduction step are Fe_3O_4, MnO, and CoO. By selecting the metal oxides, or perhaps mixed metal oxides, it may be possible to tailor the thermodynamics to a particular temperature range, perhaps enabling application to nuclear power sources or solar power towers. Thus mixed metal oxides, e.g. ferrites of cobalt, nickel, manganese, etc. and similar materials are also of interest as are other families of materials metals with numerous possible valence states such as vanadium, molybdenum, niobium, chrome, tungsten, and cerium-oxides.

Tables 1 and 2 show the thermodynamics of water splitting with a hybrid iron oxide (hematite) cycle. Table 1a showing the reduction of magnetite is provided as a baseline comparison. Clearly, the thermal reduction of hematite is far easier to accomplish. Table 2 shows that only about 10.6 kcal would be needed in a hematite/magnetite hybrid cell where the anode is chemically active whereas about 56.7 kcal of electrical energy is needed to electrochemically split water at room temperature with the traditional inert anode used in electrolyzers; the minimum voltage is reduced to about 0.23 Volts from 1.23 Volts. Tables 3 and 4 show similar calculations with cobalt oxide and Tables 5 and 6 show calculations for one particular manganese oxide couple. For cobalt, the thermal reduction temperature is significantly reduced while the cell voltage is 0.38 Volts, which is still significantly less than needed to electrolyze water directly. For the manganese oxide couple the cell voltage is also about 0.38 volts.

TABLE 1

Thermodynamics of hematite reduction $3Fe_2O_3 = 2Fe_3O_4 + ½O_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	55.509	31.723	46.844
100.000	55.676	32.213	43.656
200.000	55.864	32.666	40.408
300.000	55.976	32.879	37.131
400.000	56.365	33.495	33.818
500.000	57.543	35.109	30.398
600.000	59.194	37.144	26.761
700.000	57.776	35.614	23.118
800.000	57.708	35.545	19.562
900.000	57.565	35.420	16.012
1000.000	57.220	35.139	12.483
1100.000	56.769	34.798	8.986
1200.000	56.286	34.459	5.524
1300.000	55.833	34.161	2.093
1400.000	55.459	33.930	−1.311

TABLE 1a

Thermodynamics of magnetite reduction $Fe_3O_4 = 3FeO + ½O_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	75.541	30.449	67.224
200.000	75.483	30.508	61.048
400.000	74.380	28.626	55.110
600.000	71.304	24.670	49.763
800.000	70.484	23.800	44.943
1000.000	70.619	23.908	40.181
1200.000	71.130	24.279	35.363
1400.000	88.982	35.116	30.228
1600.000	56.815	17.941	23.208
1800.000	57.297	18.186	19.595
2000.000	57.789	18.412	15.935

TABLE 2

Thermodynamics of water dissociation with magnetite $2Fe_3O_4 + H_2O = 3Fe_2O_3 + H_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	14.431	13.226	10.818
100.000	12.068	5.108	10.161
200.000	11.064	2.722	9.775
300.000	9.895	0.496	9.611
400.000	7.844	−2.786	9.719
500.000	4.961	−6.762	10.189
600.000	1.621	−10.851	11.096
700.000	1.367	−11.134	12.202
800.000	−0.223	−12.687	13.393
900.000	−1.723	−14.026	14.732
1000.000	−3.008	−15.078	16.189

TABLE 3

Thermodynamics of cobalt oxide reduction $Co_3O_4 = 3CoO + ½O_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	46.532	33.919	37.267
100.000	47.737	37.726	33.659
200.000	48.516	39.590	29.784
300.000	49.020	40.564	25.770
400.000	49.299	41.017	21.688
500.000	49.365	41.112	17.579
600.000	49.214	40.932	13.475
700.000	48.837	40.525	9.400
800.000	48.218	39.922	5.376
900.000	47.343	39.143	1.422
1000.000	46.193	38.204	−2.447
1100.000	44.750	37.115	−6.214
1200.000	42.997	35.884	−9.865
1300.000	40.914	34.517	−13.387
1400.000	38.483	33.020	−16.765

TABLE 4

Thermodynamics of water dissociation with $3CoO + H_2O(g) = Co_3O_4 + H_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	11.208	−23.507	17.629
100.000	10.238	−26.580	20.156
200.000	9.684	−27.908	22.889
300.000	9.396	−28.469	25.712
400.000	9.323	−28.590	28.568
500.000	9.453	−28.413	31.421
600.000	9.786	−28.010	34.243
700.000	10.332	−27.420	37.016
800.000	11.103	−26.668	39.722

TABLE 4-continued

Thermodynamics of water dissociation with $3CoO + H_2O(g) = Co_3O_4 + H_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
900.000	12.114	−25.769	42.345
1000.000	13.382	−24.734	44.871

TABLE 5

Thermodynamics of manganese oxide reduction $2Mn_2O_3 = 4MnO + O_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	44.529	26.551	37.277
100.000	44.597	26.773	34.607
200.000	44.571	26.713	31.931
300.000	44.493	26.566	29.267
400.000	44.379	26.382	26.619
500.000	44.231	26.178	23.991
600.000	44.049	25.957	21.384
700.000	43.829	25.720	18.800
800.000	43.570	25.466	16.241
900.000	43.266	25.195	13.708
1000.000	42.913	24.907	11.203
1100.000	42.509	24.602	8.727
1200.000	42.048	24.278	6.283
1300.000	41.527	23.936	3.872
1400.000	40.942	23.576	1.496
1500.000	40.289	23.197	−0.843

TABLE 6

Thermodynamics of water dissociation with $2MnO + H_2O(g) = Mn_2O_3 + H_2(g)$

T, ° C.	deltaH, kcal	deltaS, cal/K	deltaG, kcal
0.000	13.210	−16.139	17.618
100.000	13.378	−15.626	19.208
200.000	13.629	−15.031	20.741
300.000	13.922	−14.470	22.216
400.000	14.243	−13.955	23.637
500.000	14.587	−13.479	25.008
600.000	14.952	−13.036	26.334
700.000	15.339	−12.615	27.616
800.000	15.752	−12.212	28.857
900.000	16.191	−11.821	30.059
1000.000	16.661	−11.437	31.222

Example Implementation Strategy:

An example implementation strategy **40** is shown in FIG. **2**. The oxygen producing step in the hybrid metal oxide cycle is thermally driven. A preferred method could be in a reactive particle receiver **42**. In the reactive particle solar receiver **42**, the oxidized particles would be directly heated and thermally reduced in an open cavity **44**, potentially in air. The reactive particle solar receiver **42** is similar to the solid particle receiver except that the particles undergo thermal reduction chemical reactions in the receiver. The particles could be recirculated within the receiver to increase residence and heat transfer times. The use of inert gas such a nitrogen (it would not require high purity) inside the reactive particle receiver/reactor cavity **46** could further drive the reaction and/or lower the temperatures required. Countercurrent flow of the metal oxide particles and inert gas in the down comer **48** of the reactive particle receiver **42** would be advantageous for driving the thermal reduction reaction with some of the sensible heat in the particles. The hot (reduced) metal oxides could be used to preheat the metal oxide feed. As shown in FIG. **2**, an alternative would be to use the sensible thermal energy to drive electricity producing Rankine or other thermodynamic cycle before being fed to the electrochemical cell. Low-grade steam exiting the Rankine cycle could also be employed as an inert sweep in the reactive solid particle receiver.

We envision that the reduced particles would be fed into the electrolyzer as a slurry in water. The slurry may also contain an electrolyte such as potassium hydroxide. This electrochemical step may be facilitated by packed bed or fluidized bed electrodes, an approach that has received a significant amount of research. In this concept the reduced metal oxide, mixed or doped with a kinetically oxygen-inert electrically conductive material, such as Ni, would be the cell's anode. The metal oxide is the active anode and the Ni is facilitating the needed electron transfer for the anodic reaction to take place, but is not chemically participating in the reaction. The required electrochemical potential needed to split water is reduced in comparison to the required potential of a traditional electrolysis of water by the chemical potential from the metal oxide. The active anode, however, is consumed as it is oxidized during the electrolysis process and would be circulated through the electrolytic cell. After leaving the electrolytic cell the reoxidized metal oxide particles would be rinsed to remove the electrolyte and dried before returning to the reactive particle receiver.

Other Embodiments

Other analogous redox reactions are candidates for a similar approach. For example, the splitting of CO_2 to CO and O_2 should be amenable to same approach and materials outlined here.

The hybrid electrochemical approach could also be used to enhance the oxidation kinetics of systems wherein the reactions are thermodynamically favorable, but are reaction rate limited.

It is contemplated that the parts and features of any one of the specific embodiments described can be interchanged with the parts and features of any other of the embodiments without departing from the spirit and scope of the present disclosure. The foregoing description discloses and describes merely exemplary embodiments of the present disclosure and is not intended to be exhaustive or to limit the disclosure to the precise form disclosed. As will be understood by those skilled in the art, the disclosure may be embodied in other specific forms, or modified or varied in light of the above teachings, without departing from the

spirit, novelty or essential characteristics of the present disclosure. Accordingly, the disclosed embodiments are intended to be illustrative, but not limiting, of the scope of the invention. The exclusive right to all modifications within the scope of this disclosure is reserved.

What is claimed is:

1. A hybrid thermochemical splitting cycle implementation comprising:

a reactive particle receiver including an open cavity;

a down comer;

a hot particle storage container;

a heat exchanger; and

an electrolyzer;

wherein oxidized particles are directly heated and thermally reduced in the open cavity.

2. The hybrid thermochemical splitting cycle implementation of claim **1**, wherein the oxidized particles are recirculated within the reactive particle receiver to increase residence and heat transfer times.

3. The hybrid thermochemical splitting cycle implementation of claim **1**, wherein particles within the reactive particle receiver are recirculated within the reactive particle receiver to increase residence time.

4. The hybrid thermochemical splitting cycle implementation of claim **1**, wherein the open cavity receives concentrated solar flux.

5. The hybrid thermochemical splitting cycle implementation of claim **1**, further comprising:

an electric power cycle in thermal connectivity with the heat exchanger that receives heat removed by the heat exchanger.

6. The hybrid thermochemical splitting cycle implementation of claim **1**, wherein the electrolyzer is configured to reoxidize an oxygen-deficient metal oxide by reducing water to produce hydrogen.

7. The hybrid thermochemical splitting cycle implementation of claim **6**, wherein the electrolyzer is further configured to receive electricity for reducing water into hydrogen.

8. The hybrid thermochemical splitting cycle implementation of claim **1**, wherein the electrolyzer is configured to reoxidize an oxygen-deficient meal oxide by reducing carbon dioxide to produce carbon monoxide.

9. The hybrid thermochemical splitting cycle implementation of claim **8**, wherein the electrolyzer is further configured to receive electricity for reducing carbon dioxide to produce hydrogen.

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