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(54) **RECOVERING THE COMPRESSION ENERGY IN GASEOUS HYDROGEN AND OXYGEN GENERATED FROM HIGH-PRESSURE WATER ELECTROLYSIS**

(75) Inventors: **Nelson A. Kelly**, Sterling Heights, MI (US); **Thomas L. Gibson**, Utica, MI (US); **David B. Ouwerkerk**, Torrance, CA (US)

Correspondence Address:

General Motors Corporation**c/o REISING, ETHINGTON, BARNES, KISSELLE, P.C.****P.O. BOX 4390****TROY, MI 48099-4390 (US)**

(73) Assignee: **GM GLOBAL TECHNOLOGY OPERATIONS, INC.**, DETROIT, MI (US)

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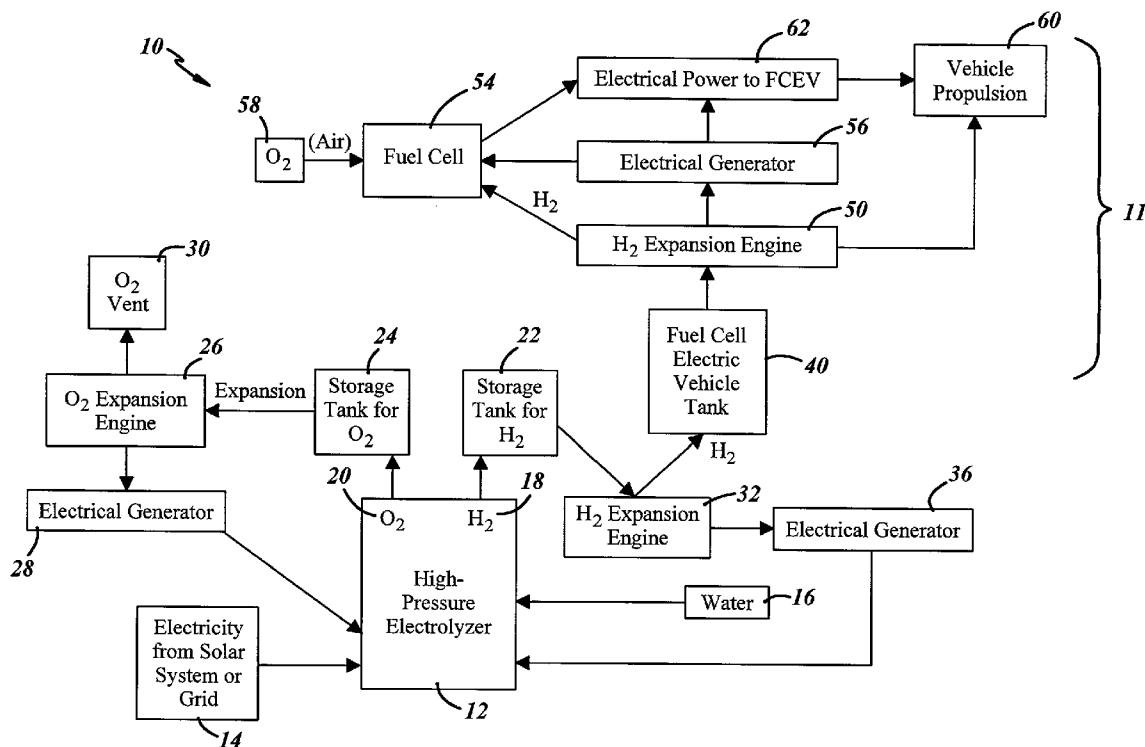
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(57) ABSTRACT

Exemplary embodiments include an apparatus, and method associated therewith, for recovering the compression energy stored in hydrogen gas and oxygen gas generated by the electrolysis of water in a high-pressure water electrolyzer. The restored compression energy may be recovered and converted to a useable form to provide power to the high-pressure water electrolyzer, or alternatively to provide usable power to a coupled system that uses high-pressure hydrogen gas or oxygen gas such as a fuel cell for an electric vehicle, or both for use in providing power to the electrolyzer and to the fuel cell electric vehicle.



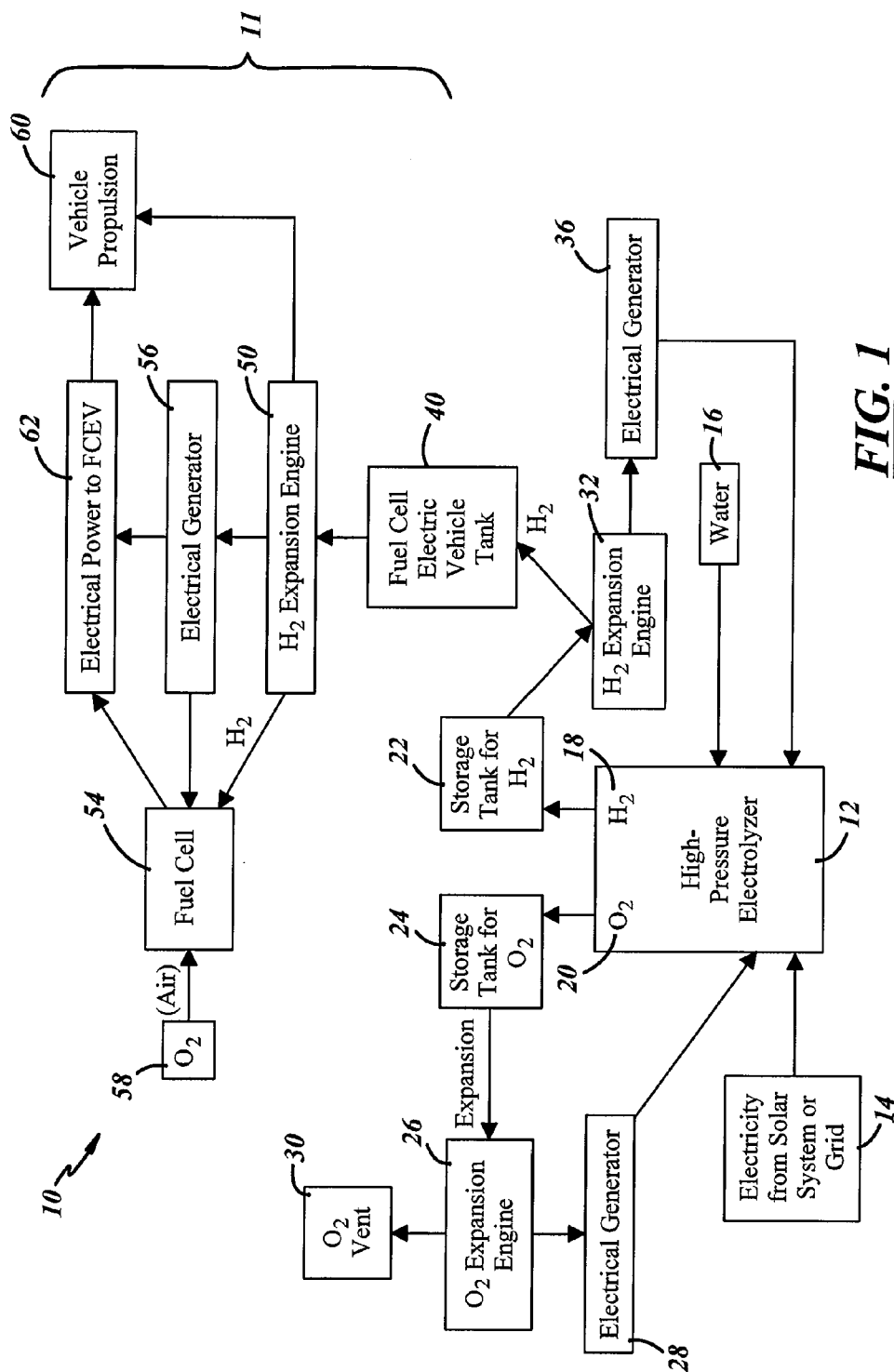


FIG. 1

RECOVERING THE COMPRESSION ENERGY IN GASEOUS HYDROGEN AND OXYGEN GENERATED FROM HIGH-PRESSURE WATER ELECTROLYSIS

TECHNICAL FIELD

[0001] The field to which the disclosure relates generally to energy recovery systems and, in particular, to the recovery of compressive energy generated during a high-pressure water electrolysis process.

BACKGROUND

[0002] Electrolyzers convert abundant, low-energy content chemicals into more valuable ones by using electricity to break down compounds into elements or simpler products. A water electrolyzer is a system of cells in which each cell contains two electrodes. In each cell water is oxidized at one electrode (called the cell anode), to produce oxygen gas, and reduced at the other electrode (called the cell cathode), to produce hydrogen gas. The oxidation-reduction reactions are driven by a direct current (DC) power source. Oxygen and hydrogen are generated in a stoichiometric ratio—two volume units of hydrogen for every one of oxygen—at a rate proportional to the applied cell current.

[0003] Water electrolysis appears to be ideally suited to making and storing hydrogen needed to power fuel cells, including specifically fuel cell powered electric vehicles. In a high-pressure water electrolyzer, hydrogen gas can be produced at sufficiently high-pressures (up to about 10,000 pounds per square inch, psi) for storage without the need for mechanical compression. Such systems, however, require significant energy input to drive the high-pressure electrolysis process. In addition, oxygen that is generated in this process generally goes unutilized, and is typically vented to the atmosphere.

SUMMARY OF EXEMPLARY EMBODIMENTS OF THE INVENTION

[0004] One exemplary embodiment includes a method and apparatus for recovering the compression energy stored in hydrogen gas and oxygen gas generated by the electrolysis of water in a high-pressure water electrolyzer.

[0005] In one exemplary embodiment, the potential energy in compressed oxygen gas generated as a by-product of electrolytic hydrogen production via water electrolysis in a high-pressure electrolyzer may be used to drive a pneumatic engine. The pneumatic engine can then drive an electrical generator to produce electricity, and the electricity generated may be used to partially power the electrolyzer that originally made the oxygen gas and hydrogen.

[0006] In another exemplary embodiment, the potential energy in compressed hydrogen gas may be recovered as expansion energy that in turn may drive an electrical generator. This electrical energy may then be used to partially power the high-pressure electrolyzer that originally made the oxygen and hydrogen gas.

[0007] In a related exemplary embodiment, the potential energy from both the compressed hydrogen gas and oxygen gas generated within the high-pressure water electrolyzer may be recovered as expansion energy that in turn may drive one or more electrical generators. This electrical energy may then be used to partially power the high-pressure water electrolyzer that originally made the oxygen and hydrogen gas.

[0008] In yet another exemplary embodiment, the expansion of hydrogen gas may also be used aboard a fuel cell electric vehicle. In this embodiment, the compressed hydrogen gas may be recovered as expansion energy that in turn may drive a mechanical electrical generator. This electrical energy may be used to partially power the fuel cell.

[0009] In still another exemplary embodiment, the expansion energy of hydrogen gas may be used directly as mechanical energy from a pneumatic engine to help propel the fuel cell electric vehicle.

[0010] In a further exemplary embodiment, the expansion energy of hydrogen gas may both be used in a hybrid fuel cell/pneumatic vehicle as both mechanical energy from a pneumatic engine to help propel the vehicle and further may be used to drive a mechanical electrical generator and may be used to power a fuel cell electric vehicle.

[0011] Other exemplary embodiments of the invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while disclosing exemplary embodiments of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Exemplary embodiments of the invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0013] FIG. 1 is a schematic flow chart of a system used to generate high-pressure hydrogen and oxygen gases using a high-pressure water electrolyzer and using the hydrogen in a fuel cell electric vehicle or stationary fuel cell with recovery of both the chemical energy of the hydrogen and the compression energy stored in the high-pressure gases in accordance with an exemplary embodiment.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0014] The following description of the embodiment(s) is merely exemplary (illustrative) in nature and is in no way intended to limit the invention, its application, or uses.

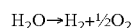
[0015] Referring now to FIG. 1, a system 10 that may generate high-pressure hydrogen gas and oxygen gas via high-pressure water electrolysis is provided in one exemplary embodiment. A portion the hydrogen gas generated may be used by a fuel cell electric vehicle 11 (or stationary fuel cell) is also illustrated within the exemplary embodiment.

[0016] The system 10 may include a high-pressure water electrolyzer 12 that may be used to generate high-pressure hydrogen gas and oxygen gas from water. The electrolyzer 12 may be powered by electricity from a solar system grid 14 or other conventional electrical powering devices (not shown).

[0017] By definition, a high-pressure electrolyzer is a water-based electrolyzer that is capable of producing hydrogen gas and oxygen gas at pressures up to about 10,000 pounds per square inch. One example of a conventional high-pressure electrolyzer 12 that may be utilized in the exemplary embodiment is the Avalance high-pressure electrolyzer (available from Avalance LLC of Milford, Conn.), which uses a unipolar alkaline (KOH) electrolyte system with cylindrical steel electrolysis cells and includes structure for balancing the hydrogen gas and oxygen gas levels and electrolyte levels to

keep the gases and electrolytes separate, as well as preventing the mixing of the hydrogen gas and oxygen gas.

[0018] Water may be introduced to the electrolyzer 12 from a holding tank 16; through the use of a high-pressure pump (not shown). The water may undergo a oxygen evolution reaction (oxidation reaction) at the electrolyzer anode (not shown) and may undergo a hydrogen evolution reaction (reduction reaction) at the electrolyzer cathode (not shown) according to the general formula:



[0019] The high-pressure hydrogen gas 18 and oxygen gas 20 produced within the electrolyzer 12 may be separately removed under pressure to a hydrogen gas storage tank 22 and oxygen gas storage tank 24, respectively. In one exemplary embodiment, the pressure of hydrogen gas 18 that is removed may approach about 10,000 pounds per square inch.

[0020] The high-pressure oxygen gas 20 may then be introduced from the storage tank 24 into an oxygen gas expansion engine 26 (pneumatic engine). The expanding oxygen gas within the oxygen expansion engine 26 may then drive an electrical generator 28 to produce electricity, and the electricity generated may be used to partially power the electrolyzer 12. The expanded gas from the pneumatic engine 26 may then vented to the atmosphere 30.

[0021] The storage of high-pressure electrolytically-produced oxygen, along with recovery of the compression energy using a oxygen gas expansion engine 26 as mechanical energy, followed by conversion of the mechanical energy into electrical energy, may increase the efficiency of a solar electrolysis process by utilizing much of the energy stored in the high-pressure oxygen. It is estimated that an energy savings of up to about three percent of the lower heating value (LHV) energy of the hydrogen gas produced by electrolysis in the electrolyzer 12 may be recovered as electrical energy by using the compression energy in the stored oxygen in the exemplary embodiment described herein (10,000 psi of stored O_2).

[0022] The hydrogen gas 18 generated in the electrolyzer 12 may be introduced from the hydrogen gas storage tank 22 to a hydrogen gas expansion engine 32 (pneumatic engine). The expansion of hydrogen gas within the hydrogen expansion engine 32 may then drive an electrical generator 36 to produce electricity, and the electricity generated may be used to power the electrolyzer 12. The expanded hydrogen gas may then be transferred to a fuel cell electric vehicle holding tank 40.

[0023] The storage of high-pressure electrolytically-produced hydrogen, along with recovery of the compression energy using a hydrogen gas expansion engine 32 as mechanical energy, followed by conversion of the mechanical energy into electrical energy, may increase the efficiency of a solar electrolysis process by utilizing much of the energy stored in the high-pressure hydrogen. It is estimated that an energy savings of up to about six percent of the lower heating value (LHV) energy of the hydrogen gas produced by electrolysis in the electrolyzer 12 may be recovered as electrical energy by using the compression energy in the stored hydrogen in the exemplary embodiment described herein (10,000 psi of stored H_2).

[0024] A fuel cell electric vehicle holding tank 40 for a fuel cell electric vehicle 11 may also be filled with expanding hydrogen gas from the hydrogen gas storage tank 22 through the gas expansion engine 32 until such time as there is an

equilibrium state in hydrogen gas pressure between the hydrogen gas storage tank 22 and the holding tank 40. This equilibrium state may preferably be tied to a predetermined hydrogen gas pressure within the holding tank 40, corresponding to a predetermined quantity of hydrogen gas. In this equilibrium state, there is little conversion of compression energy to mechanical energy occurring in the hydrogen gas expansion engine 32. The subsequent release of hydrogen gas from the holding tank 40 to the fuel cell 54 as described below allows additional hydrogen gas to be filled from the hydrogen gas storage tank 22 through the engine 32 to maintain the equilibrium state. In the exemplary embodiment shown herein, the hydrogen gas pressure in the holding tank 40 may be maintained at about 10,000 psi.

[0025] The holding tank 40 may hold the compressed hydrogen gas on a vehicle 11 until such time as it is needed in the fuel cell 54 to generate electric power to propel the vehicle 11 and/or provide power to a particular vehicle component. When needed, the compressed hydrogen gas contained in the holding tank 40 may be expanded within the second hydrogen expansion engine 50 and released to the fuel cell 54.

[0026] In fuel-cell conversion, the hydrogen gas entering the fuel cell 54 is reacted with oxygen (which may enter the fuel cell 54 from a storage tank 58 or from an ambient setting), in a stoichiometric ratio, to produce water and electricity, the latter of which may be used to power an electric traction motor 62. The electric traction motor 62 may convert the electrical energy to mechanical energy to propel the vehicle 11 again as shown in box 60. Additional electrical energy for the electric traction motor 62 may be provided by the pneumatically-powered electrical generator 56.

[0027] The expanding hydrogen gas entering the second hydrogen expansion engine 50 from the holding tank 40 may also be used to drive an electrical generator 56 and/or may also be fed, in the form of mechanical energy, to the wheels of the fuel-cell electric vehicle to propel the vehicle 11, as shown in box 60.

[0028] Thus, the exemplary embodiment illustrated herein provides a method and apparatus for increasing the efficiency of the high-pressure hydrogen generation and utilization process by recovering and utilizing the compression energy stored in high-pressure hydrogen gas and oxygen gas in ways to reduce energy costs associated with their production and end use.

[0029] The above description of embodiments of the invention is merely exemplary in nature and, thus, variations thereof are not to be regarded as a departure from the spirit and scope of the invention.

What is claimed is:

1. A system comprising:

a water electrolyzer including a water inlet and an oxygen gas outlet;
an oxygen gas expansion engine fluidically coupled to said oxygen gas outlet; and
an electrical generator coupled to said oxygen gas expansion engine and electrically coupled to said water electrolyzer.

2. The system of claim 1, wherein high-pressure oxygen gas produced in said water electrolyzer is expanded within said oxygen gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

3. The system of claim 1 further comprising an oxygen gas storage tank fluidically coupled to and between said oxygen gas outlet and said oxygen gas expansion engine.

4. The system of claim 1 further comprising a hydrogen gas expansion engine fluidically coupled to a hydrogen gas outlet on said high-pressure water electrolyzer, said hydrogen gas expansion engine also being coupled to said electrical generator.

5. The system of claim 4, wherein high-pressure hydrogen gas produced in said water electrolyzer is expanded within said hydrogen gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

6. The system of claim 1 further comprising:

a hydrogen gas expansion engine fluidically coupled to said hydrogen gas outlet; and

a second electrical generator coupled to said hydrogen gas expansion engine and electrically coupled to said water electrolyzer.

7. The system of claim 6, wherein high-pressure hydrogen gas produced in said water electrolyzer is expanded within said hydrogen gas expansion engine to drive said second electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

8. The system of claim 1 further comprising a hydrogen gas storage tank fluidically coupled to and between said hydrogen gas outlet and said hydrogen gas expansion engine.

9. The system of claim 8 further comprising:

a fuel cell electric vehicle fluidically coupled to said hydrogen gas storage tank.

10. A system comprising:

a water electrolyzer including a water inlet and a hydrogen gas outlet;

a hydrogen gas expansion engine fluidically coupled to said hydrogen gas outlet; and

an electrical generator coupled to said hydrogen gas expansion engine and electrically coupled to said water electrolyzer.

11. The system of claim 10, wherein high-pressure hydrogen gas produced in said water electrolyzer is expanded within said hydrogen gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

12. The system of claim 10 further comprising a hydrogen gas storage tank fluidically coupled to and between said hydrogen gas outlet and said hydrogen gas expansion engine.

13. The system of claim 10 further comprising:

a fuel cell electric vehicle fluidically coupled to said hydrogen gas storage tank.

14. A system comprising:

a water electrolyzer for converting water to a high-pressure gas;

a gas storage tank coupled to said water electrolyzer;

a gas expansion engine fluidically coupled to said gas storage tank; and

an electrical generator coupled to said gas expansion engine and electrically coupled to said water electrolyzer, wherein said high-pressure gas produced in said water electrolyzer is expanded within said gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

15. The system of claim 14, wherein said high-pressure gas comprises high-pressure hydrogen gas and high-pressure oxygen gas.

16. The system of claim 15, wherein said high-pressure hydrogen gas exits said water electrolyzer through a hydrogen gas outlet to a hydrogen gas storage tank, said hydrogen gas storage tank being coupled to a hydrogen gas expansion engine that is electrically coupled to said electrical generator, wherein said high-pressure hydrogen gas is expanded within said hydrogen gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

17. The system of claim 15, wherein said high-pressure oxygen gas exits said water electrolyzer through an oxygen gas outlet to an oxygen gas storage tank, said oxygen gas storage tank being coupled to an oxygen gas expansion engine that is electrically coupled to said electrical generator, wherein said high-pressure oxygen gas is expanded within said oxygen gas expansion engine to drive said electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said water electrolyzer.

18. The system of claim 16 further comprising:

a fuel cell electric vehicle coupled to said hydrogen gas storage tank, said fuel cell electric vehicle including a fuel cell hydrogen gas storage tank, a fuel cell hydrogen gas expansion engine and a fuel cell;

wherein high-pressure hydrogen gas contained within said hydrogen gas storage tank may be delivered to said fuel cell hydrogen gas storage tank and expanded with said hydrogen gas expansion engine to provide a quantity of hydrogen gas to said fuel cell.

19. The system of claim 18, wherein said fuel cell electric vehicle further comprises an electrical generator coupled to said fuel cell hydrogen gas expansion engine, wherein said high-pressure hydrogen gas is expanded within said fuel cell hydrogen gas expansion engine to drive said fuel cell electrical generator to produce electricity, said produced electricity thereafter used to aid in powering said fuel cell electric vehicle.

20. The system of claim 19 further comprising:

an electric traction motor coupled to said fuel cell, said electric traction motor aiding in propelling said fuel cell electric vehicle.

21. The system of claim 20 further comprising a fuel cell electrical generator electrically coupled to said electric traction motor, wherein a portion of said electricity is used to aid in driving said electric traction motor.

22. The system of claim 18, wherein a portion of the mechanical energy produced by expanding said high-pressure hydrogen gas within said fuel cell hydrogen gas expansion engine is used to propel said fuel cell electric vehicle.

23. A method for partially powering a high-pressure water electrolyzer, the method comprising:

providing a high-pressure water electrolyzer having a water inlet and a gas outlet;

coupling said gas outlet to a gas expansion engine;

coupling said gas expansion engine to an electrical generator;

electrically coupling said electrical generator to said high-pressure water electrolyzer;

introducing a quantity of water within said high-pressure water electrolyzer;

generating a quantity of high-pressure gas from said quantity of water within said high-pressure water electrolyzer;

introducing a portion of said high-pressure gas to said gas expansion engine; and

expanding said portion of high-pressure gas within said gas expansion engine, wherein the expansion of said high-pressure gas drives said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

24. The method of claim **23**, wherein generating a quantity of high-pressure gas, introducing a portion of high-pressure gas, and expanding said portion of high-pressure gas comprises:

generating a quantity of high-pressure hydrogen gas from said quantity of water within said high-pressure water electrolyzer; introducing a portion of said high-pressure hydrogen gas to a hydrogen gas expansion engine through a hydrogen gas outlet; and expanding said portion of said high hydrogen pressure gas within said hydrogen gas expansion engine, wherein the expansion of said high-pressure hydrogen gas drives said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

25. The method of claim **24**, wherein generating a quantity of high-pressure gas, introducing a portion of high-pressure gas, and expanding said portion of high-pressure gas further comprises: generating a quantity of high-pressure oxygen gas from said quantity of water within said high-pressure water electrolyzer; introducing a portion of said high-pressure oxygen gas to an oxygen gas expansion engine through an oxygen gas outlet; and

expanding said portion of high-pressure oxygen gas within said oxygen gas expansion engine, wherein the expansion of said high-pressure oxygen gas drives said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

26. The method of claim **25**, wherein said electrical generator comprises a pair of electrical generators, one of said pair of electrical generators being coupled to said hydrogen gas expansion engine and the other of said pair of electrical generators being coupled to said oxygen gas expansion engine;

wherein the expansion of said high-pressure hydrogen gas drives said one of said pair of electrical generators to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water; and

wherein the expansion of said high-pressure oxygen gas drives said other of said pair of electrical generators to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

27. The method of claim **24**, wherein generating a quantity of high-pressure gas, introducing a portion of high-pressure gas, and expanding said portion of high-pressure gas comprises:

generating a quantity of high-pressure oxygen gas from said quantity of water within said high-pressure water electrolyzer;

introducing a portion of said high-pressure oxygen gas to said oxygen gas expansion engine through an oxygen gas outlet; and

expanding said portion of high-pressure oxygen gas within said oxygen gas expansion engine, wherein the expansion of said high-pressure oxygen gas drives said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

28. The method of claim **24** further comprising:

coupling a high-pressure hydrogen storage tank between said hydrogen gas outlet and said hydrogen gas expansion engine.

29. The method of claim **28** further comprising:

coupling said hydrogen gas expansion engine to a fuel cell hydrogen gas storage tank on a fuel cell electric vehicle having a fuel cell;

introducing a quantity of said high-pressure hydrogen gas from said high-pressure hydrogen gas storage tank through said hydrogen gas expansion engine to said fuel cell hydrogen gas storage tank to achieve a first hydrogen gas pressure within said fuel cell hydrogen gas storage tank;

wherein the introduction of said quantity of high-pressure hydrogen gas to said fuel cell hydrogen gas storage tank is accomplished by first expanding said quantity of high-pressure hydrogen gas within said hydrogen gas expansion engine, therein driving said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

30. The method of claim **29**, further comprising:

releasing a first portion of said quantity of hydrogen gas from said fuel cell hydrogen gas storage tank to said fuel cell; and

substantially simultaneously introducing a corresponding portion of said high-pressure hydrogen gas from said high-pressure hydrogen gas storage tank through said hydrogen gas expansion engine to said fuel cell hydrogen gas storage tank to maintain said first hydrogen gas pressure within said fuel cell hydrogen gas storage tank;

wherein the introduction of said corresponding portion of said high-pressure hydrogen gas to said fuel cell hydrogen gas storage tank is accomplished by first expanding said corresponding portion of high-pressure hydrogen gas within said hydrogen gas expansion engine, therein driving said electrical generator to produce electricity, wherein said electricity is introduced to said high-pressure water electrolyzer to partially drive said generation of high-pressure gas from said quantity of water.

31. The method of claim **30**, wherein releasing a first portion of said quantity of hydrogen gas from said fuel cell hydrogen gas storage tank to said fuel cell further comprises:

expanding said first portion of said quantity of hydrogen gas within a fuel cell hydrogen gas expansion engine; and

introducing at least a portion of said first portion of said quantity of hydrogen gas with a hydrogen gas inlet on said fuel cell.

32. The method of claim **31**, wherein the expansion of said first portion of said hydrogen gas within said fuel cell hydrogen gas expansion engines drives a fuel cell electrical gen-

erator to produce electricity, wherein said electricity is used to power said fuel cell electric vehicle.

33. The method of claim **32**, wherein said electricity may also be used to power one or more vehicle components on said fuel cell electric vehicle.

34. The method of claim **31**, wherein the expansion of said first portion of said hydrogen gas within said fuel cell hydrogen gas expansion engines is converted to mechanical energy to propel said fuel cell electric vehicle.

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