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SYSTEM AND METHOD FOR TRANSPORT VEHICLES USING RECYCLABLE FUELS

Abstract

Provided are systems and methods for transport vehicles using recyclable metallic fuels. The method includes capturing fuel products, including a metal oxide and unburnt fuel from the combustion of a metallic fuel, storing the unburnt metallic fuel and the fuel products, and recycling the metal oxide to recreate the metallic fuel and/or byproducts. Heat generated by the combustion and/or sintering of the metallic fuel may be transferred to a working fluid to drive the production of electricity and/or to provide propulsion in land, air and water vehicles and spacecraft. Furthermore, the thermal energy harvesting system may be used to generate electricity. The system includes a thermal (heat) engine having an induction heating assembly for heating the metallic fuel. Processes for complete combustion of the metallic fuel and recycling the metallic fuel in a sintering loop are described.

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Background/Summary

TECHNICAL FIELD

[0001] The embodiments disclosed herein relate to fuel for propulsion and/or powering systems and, in particular to systems and methods for propulsion and power generation in transport vehicles using recyclable fuels.

INTRODUCTION

[0002] Dependence on fossil fuels is driving an environmental crisis by increasing concentrations of atmospheric greenhouse gases, which studies link to elevating average global temperatures and accelerating disruptive climate change. On the other hand, standards of living are directly correlated with per capita energy consumption, with the result that the desire to improve quality of life prompts consumption of higher and higher levels of energy per person. These circumstances, coupled with a continually growing population, consequently drive global energy requirements for clean renewable energy sources to be scaled up to meet demand while simultaneously replacing fossil fuels use for the largest energy needs including transportation and/or electrical and/or thermal power generation.

[0003] In addition, in-space powering and propulsion of space systems using existing, conventional fuels (including solid and or liquid propellant) brought from Earth are costly and impractical systems and methods for use over large distances or for long time periods given the weight/volume requirements and other challenges of storing fuel onboard. Transporting fuel to from Earth to orbit, and point to point travel in space, is also problematic given the high volatility of most conventional fuels and is further limited by size/weight requirements of spacecraft and/or launch vehicles. A further limitation is that the range of a spacecraft is restricted by the amount of fuel carried onboard, and once fuel reserves are depleted, the spacecraft can no longer propel or maneuver itself.

[0004] Fuels such as metallic fuels can be used for heating and combustion as an alternative energy source to meet energy demands on Earth and in Space. Metals have high energy densities and as such can also be used in many batteries, as energetic materials, and/or as propellants. Oxidation of metal powders can be used as an efficient energetic carrier and source for a number of applications. The exothermic reaction between the metal and an oxidizer release heat and generates products such as metal oxides. Metal oxides can themselves also be combusted in the presence of a metal in the form of nano- and or micro-thermites. In an implementation, by using the energy release to create heat to accelerate a fluid within a nozzle and/or create heat for a heat engine, thrust may be generated. In another implementation, by using the energy release to heat a fluid within an electrical and/or thermal power generation system, power may be generated. In more general cases, a metal and an oxidizer, often air and/or water, is used as the carrier fluid, and as the source of oxidation of the metal. In other cases, the fuel and oxidizer, in the form of a thermite, can be both located in a metallic particle (for example a metal oxide coat on the outside of a metal particle) and or combusted providing heat to a carrier fluid. In either case these can be referred to as the metallic fuels (such as metal, metallic, and/or energetic particles, thermites and/or micro, and/or nano-thermites, or the like).

[0005] Metallic fuels may contain energetic particles which are made up of a fuel and an oxidizer —typically a metal and a metal oxide, respectively. Nanothermites are composed of both the oxidizer and fuel compose each particle—which are on the scale of 100 nanometers or below—the energy release per mass of particle is very large. In an implementation, using metallic fuel propellant including nanothermites or microthermites, or a combination thereof, may be used in any inert carrier gas and or liquid to disperse the propellant within the combustion chamber for an effective heating and/or combustion, leading to controllable power and/or thrust generation.

[0006] Metallic fuels (e.g., thermites, microthermites, nanothermites) have high energy density, and when mixed with an inert gas and/or liquid carrier fluid, are generally safer to handle and transport than conventional fuels. They can be synthesized and manufactured, and transported to be used and/or stored for future use. They are present in abundance on Earth and in Space. Propellants/fuel can be produced, stored and transported for dispatchable power. Stored energy can be in the form of fuels that can be used to generate power and propulsion.

[0007] Metallic fuels can be heated/combusted in a thermal power plant to generate steam to drive the production of electricity. Metallic fuels can also be combusted in a vehicle engine for propulsion. Products of nanothermite reactions are themselves a clean energy source of metals and/or metal oxides that can be captured, used and/or recycled. The products and/or byproducts of heating and combustion of fuels may be captured and recycled using terrestrial power generation systems employing renewable energy sources (e.g., solar, wind, thermal, nuclear, power beaming or the like).

[0008] Accordingly, there is a need for new systems and methods for transport vehicles to use recyclable metallic fuels for propulsion and power generation.

SUMMARY

[0009] Provided is a method for producing electricity and propulsion from recyclable metallic fuels. The method includes inductively heating a metallic fuel, causing at least partial combustion of the metallic fuel, transferring heat from the at least partial combustion of the metallic fuel to a working fluid to generate steam, using the steam to drive generation of electricity, and using the steam to drive propulsion of a vehicle.

[0010] The metallic fuel may be one or more of: a nanothermite, a microthermite and thermite. The metallic fuel may include a metal and an oxidizer. The oxidizer may be a second metal oxide.

[0011] The method may further include capturing fuel products and unburnt fuel from incomplete combustion of the metallic fuel, wherein the fuel products include a first metal oxide, directing the unburnt metallic fuel and the fuel products to storage and/or further oxidation, and recycling the first metal oxide to recreate the metallic fuel and/or other products.

[0012] The fuel products may further include a metal that is oxidizable for heating and/or combustion.

[0013] The method may further include inductively generating electricity using heat from the unburnt metallic fuel and the fuel products.

[0014] The method may further include recycling the fuel products by one or more chemical processes to produce the other products.

[0015] The one or more chemical processes may include one or more of: hydrogenation, methanation, carbothermal reduction and electrolysis.

[0016] The metallic fuel may be heterogeneous comprising metallic particulates surrounded by a binder. The binder may be a nanocomposite hydrogel.

[0017] The metallic fuel may be heterogeneous comprising metallic particles and a catalyst for catalytic oxidation of the metallic particles or catalytic reduction of the fuel byproducts.

[0018] The catalyst may be stimuli-responsive being chemically, mechanically, magnetically and or thermally activatable.

[0019] Energy for the one or more chemical processes may be provided by inductive-coupled and/or magnetic resonance wireless energy transmission.
[0020] The method may further include synthesizing the metallic fuel from a plurality of fuel sources harvested from the Earth, Moon, Mars, other planets, asteroids, planetoids, other celestial bodies, or a combination thereof.
[0021] The method may further include controlling volumetric heating of the metallic fuel to regulate combustion.
[0022] The vehicle may be one of: a land vehicle, an aerial vehicle and a water vehicle.
[0023] Provided is a vehicle configured to use a recyclable metallic fuel for propulsion. The vehicle includes a fuel tank for storing the metallic fuel, a water source, a mixing tank, for mixing the metallic fuel and water to form a slurry, a heat engine having an induction heating assembly, wherein the slurry is inductively heated in the heat engine causing at least partial combustion of the metallic fuel, a closed loop heat transfer system for transferring heat from the at least partial combustion of the metallic fuel to generate steam, and a propulsion system connected to the heat transfer system, wherein the propulsion system is driven by the steam to move the vehicle.
[0024] The vehicle may further include an electrical generator driven by the steam to produce electricity for powering onboard systems.
[0025] The vehicle may further include a thermoelectric system connected to the heat engine to passively capture and convert excess heat from the at least partial combustion of the metallic fuel into electricity.
[0026] The vehicle may further include at least one combustion chamber for combusting the metallic fuel, at least one reaction chamber for generating thermal power using heat from unburnt metallic fuel and fuel products, at least one storage system for capturing the unburnt metallic fuel and the fuel products, and at least one recycling system for directing the captured unburnt metallic fuel and/or the fuel products to the at least one combustion chamber and/or the at least one reaction chamber.
[0027] The vehicle may further include one or more storage tanks for storing the unburnt metallic fuel and the fuel products.
[0028] The vehicle may further include a second fuel recycling system comprising: a second reaction chamber for reducing the fuel byproducts by one or more reductive processes to regenerate the metallic fuel, and a second recycling system for directing the fuel byproducts from the at least one storage system to the second reaction chamber.
[0029] The vehicle may further include one or more of: rectennas and solar panels, for receiving energy wirelessly, wherein the energy may be used to power the induction heating assembly.
[0030] The vehicle may further include a magnetic induction coil.
[0031] The vehicle may further include a temperature regulating system for controlling the volumetric heating of the metallic fuel in the heat engine.
[0032] The vehicle may further include a second fuel tank for storing a secondary fuel, and the secondary fuel is combusted with the metallic fuel in the heat engine.
[0033] The secondary fuel may be a hydrocarbon.
[0034] The vehicle may be one of: a land vehicle, an aerial vehicle, a water vehicle and a spacecraft.
[0035] Other aspects and features will become apparent, to those ordinarily skilled in the art, upon review of the following description of some exemplary embodiments.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0036] The drawings included herewith are for illustrating various examples of articles, methods,

and apparatuses of the present specification. In the drawings:
[0037] FIG. **1**A is diagram of fuel recycling for power and propulsion, according to an embodiment;
[0038] FIG. **1**B is a diagram of in-space fuel recycling, according to an embodiment;
[0039] FIG. **1**C is a diagram of fuel recycling to produce useful byproducts, according to an embodiment;
[0040] FIG. **1**D is chemical equations for reductive processes;
[0041] FIG. **1**E is a diagram of in-situ (in-space) resource utilization process for regolith synthesis and transformation;
[0042] FIG. **2** is diagrams of exemplary thermites;
[0043] FIG. **3** is a diagram of nanocomposite hydrogel synthesis;
[0044] FIG. **4**A is a diagram of a heterogeneous nanothermite fuel;
[0045] FIG. **4**B is a diagram of combustion of the nanothermite fuel in FIG. **4**A;
[0046] FIG. **5** is diagrams of packing configurations for fuel particles;
[0047] FIG. **6** is a diagram of the electromagnetic spectrum showing wavelengths for wireless energy transmission;
[0048] FIG. **7** a diagram of power and data network topologies for wirelessly powering a three-dimensional array of vehicles, according to several embodiments;
[0049] FIG. **8** is a diagram of a deployable data hub system for use in point-to-point data transmission, according to an embodiment;
[0050] FIG. **9** is a diagram of a rapidly deployable power hub system for use in point-to-point wireless power transmission, according to an embodiment;
[0051] FIG. **10** is a diagram of a boiler ground-based system, according to an embodiment;
[0052] FIG. **11** is a diagram of a boiler in-flight system, according to an embodiment;
[0053] FIG. **12** a recyclable fuel powered space-to-earth wireless power and data transmission system, according to an embodiment;
[0054] FIGS. **13**A-**13**B are diagrams of a point-to-point payload transfer system, according to an embodiment;
[0055] FIGS. **14**A-**14**B are diagrams of cycler systems implementing metallic fuel recycling, according to several embodiments;
[0056] FIG. **15** is a diagram of a point-to-point beam riding system, according to an embodiment;
[0057] FIG. **16** is a diagram of point-to-point wireless power transmission for wildlife management applications, according to an embodiment;
[0058] FIG. **17** is a diagram of a multi-directional beam riding system, according to an embodiment;
[0059] FIG. **18** is a diagram of inductive-coupled magnetic resonance wireless power transfer between two aerial craft, according to an embodiment;
[0060] FIGS. **19-20** are diagrams of wireless power transfer systems for charging airborne fleets of UAVs, according to several embodiments;
[0061] FIG. **21** is a diagram of a hybrid wireless power transmission system, according to an embodiment;
[0062] FIG. **22** are diagrams of system architectures for wireless power and data transmission, according to several embodiments;
[0063] FIG. **23** is a diagram of recording wireless power and data transfer in a blockchain, according to an embodiment;
[0064] FIGS. **24-25** are diagrams of a microwave elevator system, according to an embodiment;
[0065] FIG. **26** is a diagram of module swapping system for aerial craft, according to an embodiment;
[0066] FIG. **27** is a diagram of an in-flight charging system for drones, according to an embodiment;

[0067] FIGS. **28-29** are diagrams of ground tethered hybrid wireless power transfer systems, according to several embodiments;
[0068] FIG. **30** is a diagram of an air-water interface application for wireless power transmission systems, according to an embodiment; and
[0069] FIG. **31** is a diagram of aerial craft connectivity with smart city infrastructure for wireless power and data transmission, according to an embodiment.

DETAILED DESCRIPTION

[0070] Various apparatuses or processes will be described below to provide an example of each claimed embodiment. No embodiment described below limits any claimed embodiment and any claimed embodiment may cover processes or apparatuses that differ from those described below. The claimed embodiments are not limited to apparatuses or processes having all of the features of any one apparatus or process described below or to features common to multiple or all of the apparatuses described below.
[0071] References herein to “fuel” and “metallic fuel” means recyclable metallic fuel (e.g., thermites), unless stated otherwise. References herein to “secondary fuel” means a fuel other than recyclable metallic fuel (e.g., hydrocarbons).
[0072] The systems and methods described herein utilize a thermal (heat) engine. Heat engines include non-combustion engines (e.g., steam engines in nuclear power plants) and combustion engines. Combustion engines include internal combustion engines, external combustion engines and air-breathing engines (e.g., rocket engines). Both internal combustion and external combustion engines may be categorized as rotary or reciprocating engines. Internal combustion rotary engines include open-cycle gas turbines and Wankel engines. External combustion rotary engines include closed-cycle gas turbines and steam engines. Internal combustion reciprocating engines include gas engines and diesel engines. External combustion reciprocating engines include Stirling engines and steam engines.
[0073] Heat engines may also be classified according to: stroke cycle operation (e.g., four stroke cycle or two stroke cycle); ignition type (e.g., spark ignition, compression ignition, laser ignition, induction, or a hybrid ignition using a combination of the aforementioned types); cooling (e.g., air cooled, water cooled, or hybrid cooling with use of metallic fuel); valve mechanism (e.g., overhead valves or overhead cams); and cylinder arrangement (e.g., in-line, V-type, horizontally opposed or horizontally mounted).
[0074] Generally, the heat engines described herein may be of any of the above engine types but configured specifically for combustion of recyclable metallic fuels and secondary fuels (e.g., hydrocarbons), such as the thrust engine disclosed in WO2020049528 having a priority date of Sep. 6, 2018 and to the same applicant, which is incorporated by reference herein, in its entirety. The heat engines described herein may be implemented in a variety of transport vehicles to provide power and propulsion. Transport vehicles incorporating a heat engine may include, but are not limited to, land vehicles (e.g., cars, motorcycles, trucks, busses, mobile homes, trains), aerial vehicles (e.g., planes, helicopters, balloons, airships/blimps, drones), water vehicles (e.g., ships, submarines) and spacecraft (e.g., rockets, satellites).
[0075] Referring to FIG. **1**A, shown therein is a diagram of fuel recycling **600** for power and propulsion. A fuel **602** is heated/combusted (oxidized) to generate energy **610** for propulsion, power, storage or transmission (dispatchable power) and waste heat **608** may be harvested to co-generate further energy **610**. Fuel products **604** generated by oxidation of the fuel **602** are captured and recycled back into usable fuel **602** by reduction. Reduction of fuel products **604** requires an input of energy **606**. It may be particularly advantageous to use terrestrial renewable energy sources to provide the input of energy **106** required for reduction of the fuel products **604**.
[0076] The fuel recycling **600** shown in FIG. **1**A may be adapted for use in vehicles. According to an embodiment, the fuel **602** (e.g., a nanothermite) is heated and/or combusted in a heat engine to provide thrust or propulsion. According to another embodiment, the fuel **602** is heated and/or

combusted to heat a working fluid within an electrical and/or thermal power generation system, and power may be generated for energy distribution. According to other embodiments, the fuel **602** is heated and/or combusted to synthesize/produce fuel by products (e.g., metal and metal oxides) which may be used for transportation, manufacturing of other byproducts and/or storage (FIG. **1**C).

[0077] Referring to FIG. **1**B, shown therein is a diagram of in-space fuel recycling **620**. A metallic fuel **622** (e.g., a nanothermite) may be burned to provide propulsion of spacecraft (rockets, non-rocket launch systems e.g., balloons, impulse drivers, or other satellite propulsion systems, etc.) and generate energy **628** for in-space applications. The metallic **622** fuel may be synthesized from in-space resources (regolith) and or space debris **624** using an input of space-based energy **626**. It may be particularly advantageous to use solar energy in space, and/or solar power satellites wherein wireless power transmission and/or power beaming are coupled to renewable energy sources to provide the input of energy **626** required for in-space reduction of space resources/debris **624**. For example, energy (electromagnetic radiation) may be beamed from earth to space to power in-space fuel recycling **620** using systems and methods for wireless power transmission, as disclosed in PCT/CA2021/050985 filed Jul. 15, 2021 and having a priority date of Jul. 15, 2020 and to the same applicant, which is incorporated by reference herein, in its entirety. In-situ resource utilization (ISRU) may also be employed to harvest regolith **624** in-space which is then transformed for in-space metallic fuel synthesis and recycling. Space debris **624** may also be recycled and turned into metallic fuels **622** and other useful byproducts using the systems and methods described. The metallic fuels **622** may be transported for use and distribution at other locations and/or stored for later use.

[0078] Referring to FIG. **1**C, fuel products **634** may be captured, transported and/or recycled. Reduction of the fuel products **634** to generate recyclable metallic fuel **632** can be achieved through known processes such as carbothermal reduction, methanation and electrolysis (see FIG. **1**D). Other processes may also be used such as hydrogenation to produce other useful “byproducts.” For example, the “Metal A Oxide” fuel product **634** may be recycled and used in other applications such as additive manufacturing, or it can be reduced into metallic fuel **632** by a process that creates other useful “byproducts” including, but not limited to hydrogen, methane, water, oxygen, or the like (see FIG. **1**E) which can be stored for other applications. Similarly, the “Metal B” fuel product **634** is itself a metallic fuel which can be further oxidized using air or water or another oxidizer for energy and power production. It should be noted that “Metal A” and “Metal B” may be different metals, or may be same metal having different oxidation states (i.e., varying valency).

[0079] Fuel **602** sources may include one or more of: reactive metal compounds (e.g., thermites, microthermites, nanothermites) (FIG. **2**); materials with magnetic properties; a mixture of layers of metals; multicoated metals with metamaterials (FIGS. **4**A, **4**B); hybrid mixtures of reactive metal compounds in liquid and inert states; in-situ space resources (e.g., regolith); ceramic precursors; conductive pastes; natural and synthetic fibers (FIG. **3**); and hydrogels (FIG. **3**). Fuel **602** sources may be in solid (powdered), liquid, or gaseous state.

[0080] Other fuel sources many include thermoplastics and/or other terrestrial waste products, such as cellulosics (e.g., toys, lamp shades, partition, shelf covers, storage boxes, ice crushers, juicer bowls, vacuum parts, tool handles, pipes, eyeglass frames), nylon (e.g., slide fasteners, combs, brushes and bristles, baby dishes, funnels, salad spoon and fork, washer gaskets), polyethylene (squeeze bottles, ice trays, toys, storage boxes, flashlights, wiring, pipes, kitchenware (film or coating, semi-rigid, rigid), vinyl (raincoats, upholstery, tiles, inflatable curtains, toys, luggage, baby clothes, records (film, sheeting, semi-rigid, rigid, coating), acrylic (bowls, trays, partitions, roofing, handbags, eyeglasses, light fixtures, table appointments, bookends, dresser sets, window glazing, picture frames), or the like.

[0081] The fuel **602** may be synthesized from one or more fuel sources by hybrid synthesis methods, including: additive manufacturing, physical mixing, chemical reactions, emissive and missive methods, vapor deposition, pyrolysism microwave-assisted synthesis, ball milling, exfoliation, sonochemical techniques, arc-discharge, or a combination thereof.

[0082] The fuel **602** may be heterogeneous having two or more components with distinct properties, for example, hard metallic particulates and a soft binder for cohesion and flow. Heterogenous fuel **602** may beneficially provide a large contact surface area and internal/external frictional resistance to flow. Heterogeneous fuel **602** may include particles of different length and size scales.

[0083] Referring to FIG. **2**, shown therein are exemplary thermites **650**, **652**, **654**. Thermites **650**, **652**, **654** are a metastable intermolecular composite made up of a fuel, typically a metal (shown in dark shading), and an oxidizer, typically a metal oxide (shown in light shading). As the thermite **650**, **652**, **654** includes both the oxidizer and metal fuel, the energy released per unit mass is very large. Thermite particles can range in size from a microthermite **650** on the scale of hundreds of micrometers to a nanothermite **652** on the scale of 100 nanometers of less. Nanometer-scale ordered thermite **654** is another variant.

[0084] Referring to FIG. **3**, shown therein is a diagram of nanocomposite hydrogel synthesis **670**. Natural or synthetic polymer sources **672** are combined with nanomaterials **674** (e.g., nanothermites) to produce nanocomposite hydrogels **676**. The resulting hydrogel **676** is mechanically strong, electrically conductive and responsive to stimuli. The hydrogel **676** may be synthesized as a simple linear-chain structure or a crosslinked structure.

[0085] Referring to FIG. **4**A, shown therein is a diagram of a heterogeneous fuel **700**. The heterogenous fuel **700** may be the fuel **602** in FIG. **1**A or metallic fuel **632** in FIG. **1**C. The fuel **700** includes a nanothermite particle **702** composed of 2×Al/Fe.sub.2O.sub.3 particles. The nanothermite particle **702** is wrapped in a binder **704** in a core-shell arrangement. The binder **704** may be a hydrogel (e.g., hydrogel **676**) or a metamaterial (e.g., a self-assembled nanomaterial, nanocarrier nanowires, aerogels, or the like). The composition of the binder **704** may be application specific.

[0086] The fuel **700** may be burned/combusted in a thermal power plant or heat engine. As shown in FIG. **4**B, an input of thermal energy causes the nanothermite particle **702** to heat or combust into individual thermite particles **706** and release thermal energy, which can propagate further combustion. The heat generated, may be converted to electric power through heat transfer and/or inductive heating. “Waste” heat may also be harvested and turned into electricity, using for example, with one or more of the following: thermionic emission, thermophotovoltaic, and or thermoelectric device or the like.

[0087] Combustion of metallic fuels produce a solid-phase fuel product. For example, in nanothermite coreshell combustion, an Aluminum/Iron Oxide coreshell is combusted producing Aluminum Oxide (Al.sub.2O.sub.3) and Iron. The Aluminum Oxide and Iron may be captured and recycled for reuse. The Aluminum Oxide may be used to additively manufacture useful products, whereas the Iron is oxidized further and used as a metal fuel, where its metal oxide products may be further captured and recycled as fuel. The captured byproducts may be recycled using renewable terrestrial energy, stored energy, energy harvested from the environment (i.e., solar) or using energy received from wireless power transmission systems.

[0088] Capturing of fuel products for storage, and recycling may be achieved using known capture techniques adapted for use on Earth and in Space. For example, on Earth, the metal oxide and the metal fuel products may be captured by gravity-separation in a reaction vessel. In space (a zero-gravity environment), the metal oxide and the metal fuel products may be mixed with an inert carrier fluid in the reaction chamber and magnetohydrodynamic separation may be performed to capture the fuel products according to charge.

[0089] Referring to FIG. **5**, shown therein are packing configurations **720**, **722**, **724** for fuel particles. Each ball (light and dark shading) represents a fuel particle. The fuel particles may be a heterogeneous fuel **700** or composite fuel particle **702**. The fuel particles may be arranged in a simple cubic packing **720**, a face-centred cubic packing **722**, or a hexagonal packing **724**. Other configurations, for example, wires, cones, spheres, torus, cylinder, cuboid, prisms, dodecahedron, icosahedrons, pyramids, or the like, are also contemplated. Depending on the application for the fuel, a particular packing configuration may be selected. A specific application may also dictate the shape, size, surface charge, surface area, surface functionally, porosity, size distribution, structure and composition of the fuel particles.

[0090] Packing of fuel particles may also provide for catalyst-based controlled release systems, wherein a catalyst is included with the fuel. The catalyst may be combined with fuel particles as a conjugate, as a matrix-based, or a membrane-based system that is stimuli-responsive, being chemically, mechanically, magnetically, or thermally activatable. The catalyst may also be self-activatable/excitable. A catalyst may be added to fuel particles by grafting, coating or layering methods.

[0091] Referring to FIG. **6**, shown therein is a diagram of the electromagnetic spectrum showing wavelengths of electromagnetic radiation **750** for wireless energy transmission for aeronautical and astronomical applications. The aeronautical application range **752** includes extremely low frequency (ELF), very low frequency (VLF), microwave, infrared, visible light and ultraviolet radiation. The astronomical application range **754** includes the wavelengths in the aeronautical application range **752** as well as x-ray, gamma and cosmic radiation. Types of radiation that are present in both the aeronautical application range **752** and the astronomical application range **754**, for example microwave radiation, may be used for combined aeronautical and astronomical applications such as ground-to-space (and space-to-ground) wireless energy transmission.

[0092] In-space applications of wireless power transmission as described herein may include directing power for recharging of space systems (i.e., satellite systems), constellation of satellites in orbit and surface operations of moon bases, rovers, drones, exploration vehicles, space architecture and other lunar structures or the like. Aspects of systems may be used for surface and subsurface operations. Aspects of systems described herein may be used to create a point-to-point network for wireless power and data transfer on bodies such as the Moon, Mars, asteroids, and Earth. Bodies may be orbited by a craft, such as a satellite that may communicate with devices or ground stations present on the surface of each body, such as to enable a large-scale wireless power and data transfer network, accessible on the surface and in the orbit of each body.

[0093] Metallic fuels may be used to power satellite propulsion systems (SPS) for maneuvers and station-keeping in a plurality of space applications including around the Earth, cislunar space, the Moon, Mars, and or other celestial bodies. Furthermore, metallic fuels may be used to generate electrical energy to power satellite on-board avionics, electronics, rectennas, solar panel deployment/realignment, and other mission-related instruments.

[0094] Each satellite has a wireless power receiving/transmitting system such as those disclosed in PCT/CA2021/050985. The satellite may receive power wirelessly beamed up from a surface-based power generation source or a stored power source to power the satellite, recharge batteries and/or recycle captured metallic fuel byproducts into usable metallic fuel using one or more fuel reduction processes (FIG. **1**D). Furthermore, the satellite may wirelessly beam power generated by combustion of metallic fuel to vehicles **338** or buildings on the surface or to another satellite.

[0095] A fleet (constellation) of satellites having wireless power systems may thus dynamically recycle fuel to recharge one another as needed. This may be particularly advantageous for free space satellite propulsion systems where other sources of power are unavailable. Similarly, a constellation of satellites in low-earth orbit, middle earth orbit or sunsynchronous orbit, other high orbits, geosynchronous earth orbit or other orbits around earth orbit may dynamically receive/transmit wireless power to recharge and/or recycle fuel without having to break orbit.

[0096] Referring to FIG. **7**, shown therein is a diagram of power and data network topologies **760** for powering a three-dimensional array of vehicles, that could be continuous like a crystalline structure, or random like a flock of birds. The vehicles may be land vehicles, water vehicles, drones, or other aerial craft, satellites, or spacecraft, hereafter referred to as nodes. The nodes may be fixed, mobile or hybrid systems including tethered systems having tethered components on the ground and in the air; or having tethered components in the air and in space; or “tug” systems of the type disclosed in PCT/CA2021/051885 filed Dec. 23, 2021 and having a priority date of Dec. 23, 2020 and to the same applicant, which is incorporated by reference herein, in its entirety. The nodes may transmit and receive power wirelessly and store the power. Charging a distributed array of nodes may be done using one or more of the network topologies **760** shown. Charing power may occur by transferring power from a power source to a node; then node to node (i.e., a power relay system) to dynamically manage power systems to optimize stored energy amongst nodes. Metallic fuels may be transported to a plurality of nodes for power generation and distribution to manage and optimize the power distribution network **760**.

[0097] Referring to FIG. **8**, shown therein is a diagram of a deployable data hub system **830** for use in point-to-point data transmission, according to an embodiment. The system **830** includes a constellation of satellites **831**, a fleet of aerial craft **832** and ground stations **833**. The satellites **831** include a heat engine to combust metallic fuel for propulsion and provide energy to power onboard systems.

[0098] In conventional systems wherein data is beamed directly from satellites **831** to ground stations **833**, the satellite **831** must be in range (i.e., above the ground station **833**) for successful data transmission. Compared to conventional systems, the system **830** is advantageous to provide an intermediary data hub in the fleet of aerial craft **832** to relay signals between the satellite **831** and the ground stations **833**. Accordingly, a satellite **431** need not be in direct range of a ground station **833** for successful data transmission and may transmit or receive data via the aerial craft **832** data hub. A further advantage is that data received from the satellite **831** may be transmitted directly from the aerial craft **832** data hub to IoT devices, vehicles, drones, etc. rather than having to pass through a ground station **833** first.

[0099] Referring to FIG. **9**, shown therein is a diagram of a rapidly deployable power hub system **840** for use in point-to-point wireless power transmission, according to an embodiment. The system **840** includes a constellation of satellites **841**, a fleet of aerial craft **842** and deployable ground stations **843**. The satellites **841** include a heat engine to combust metallic fuel for propulsion and provide energy to power onboard systems. The satellites **841** include transmitters to beam EM radiation down toward the earth from the power generated by the combustion of metallic fuel. The fleet of aerial craft **842** are positioned or tethered at an intermediate altitude between the satellite **841** and ground stations **843**. The aerial craft **842** include arrays of EM radiation transmitters and receivers (including rectennas). The aerial craft **842** receive the radiation beamed down from the satellite **841** and retransmit the radiation downward toward the earth.

[0100] The deployable ground stations **843** may be additively manufactured, deployable structures to house personnel, and other materials. The deployable ground stations **843** include arrays of rectennas to collect the radiation beamed downward from the aerial craft **842**. The deployable ground stations **843** are preferable dome shaped to provide maximal area for deployment of the arrays of rectennas to receive beamed radiation from the aerial craft. The system **840** may be advantageously used to generate power in remote areas where power availability is low or when a local electrical grid is down. Alternatively, the system **840** may be used to augment available energy.

[0101] It should be noted that the systems shown in FIGS. **7-9** may be implemented for ground-to-space or space-to-ground power and data transmission on any planetary or astronomical body of sufficient size, including, but not limited to the Earth, the Moon, Mars, and asteroids. In addition, in embodiments wherein energy is transmitted from the ground up to satellites, a ground thermal power plant may combust metallic fuel to generate power which is transmitted upward.

[0102] Referring to FIG. **10**, shown therein is a diagram of a ground-based recyclable fuel system **400**, according to an embodiment. The system **400** may be implemented in a ground-based thermal power plant to generate power, or in a vehicle to generate power and propulsion. The system **400** includes a heat engine **402** for combusting metallic fuel **406** (e.g., nanothermites) to generate steam. The fuel **406** is stored in a tank and is mixed with water **408** to form a slurry **404** which is fed into the heat engine **402**. The water **408** may act as a working fluid that retains the heat from the combustion of the fuel **406**, which may then be used to drive the production of electricity or provide propulsion. According to some embodiments, the heat in the working fluid may be used to boil water and generate steam to drive a generator to produce electricity. According to other embodiments, the steam generated may drive a steam engine of a vehicle to provide propulsion.

[0103] The heat engine **402** includes an induction heating assembly for heating the slurry **404** to combust the fuel **406**. For example, the induction heating assembly may produce eddy currents in the slurry **404** and heat the fuel **406**. Once combustion of the fuel **406** commences, hysteresis may provide sufficient heat for continued combustion. Generally, a combination of induction heating and hysteresis may be used to ensure an appropriate amount of heat is maintained in the heat engine **402** for combustion. Other electromagnetic radiation such as microwave, ultrasonic, ultraviolet or lasers may be used to augment or tune the combustion in the heat engine **402**.

[0104] In the heat engine **402**, heat transfer to a working fluid may be caused by complete combustion of the fuel **406** or through convection by means of sintering, where the metallic fuel **406** is heated but does not reach combustion temperature. The heat engine **402** may employ a combustion/sintering process whereby fuel **406** is preheated by sintering and then transferred to a combustion chamber.

[0105] Full combustion of the fuel **406** may occur via multi-stage combustion, where the products of a first combustion become the reactants in a second combustion. Multi-stage combustion may be achieved by looping combustion reactions or looping sintering processes, or a combination of the two, as described below.

[0106] Convection from the sintering the fuel **406** may also transfer heat to a working fluid (i.e., water **408**) to drive the production of electricity or to provide propulsion. Beneficially, sintering of the fuel **406**, may provide sufficient heat to cause a phase change in the working fluid, without requiring complete combustion of the fuel **406**. As such, the fuel **406** may be sintered to transfer heat by convention to the working fluid, then cooled and re-sintered in a loop to drive generation of electricity or to provide propulsion. The heat engine **402** may include multiple reaction chambers, where combustion of fuel **406** in a combustion chamber may be coupled to a sintering loop in a reaction chamber. Advantageously, the metallic fuel itself may be used as a coolant to regulate convection during sintering loops by introducing fresh “cool”metallic fuel into the reaction chamber, rather than using air, water or other means for cooling.

[0107] The system **400** may further include a thermal energy harvesting system (not shown) connected to the heat engine **402** to capture and convert excess heat or thermal energy into electricity directly (i.e., without use of a working fluid). The thermal energy harvesting system may include one or more of the following systems: thermophotovoltaic cells and or thermoelectric devices adjacent to around the heat engine **402**, such as Peltier devices connected to the heat engine **402**, and or use of thermionic emission.

[0108] FIG. **11** is a diagram of an in-flight recyclable fuel system **420**, according to an embodiment. The system **420** is substantially similar to the system **400** in FIG. **10**, however the system **420** is operably connected to an aerial craft, for example, a balloon **430** to drive propulsion. The fuel **426**, water **428**, slurry **424** and heat engine **422** may be contained within a gondola of the balloon **430**. Steam may be generated in a closed loop by the combustion and/or sintering of the fuel **426** and may be used to power propulsion of the balloon **430**. When the steam cools, the condensed water drains down and may be captured for reuse. Metal-based materials may be used to harvest water to drive processes.

[0109] Generally, the systems **400**, **420** shown in FIGS. **10** and **11**, respectively, may be adapted for use in any vehicle, not limited to land vehicles, aerial vehicles, water vehicles and spacecraft.

Furthermore, the systems **400**, **420** may be implemented as a hybrid system that can use exclusively recyclable metallic fuel or use a combination of metallic fuel, as a primary fuel source, in combination with secondary fuels (e.g., hydrocarbons). In such a hybrid system, the heat engine **402** may be configured to combust a mixture of the metallic fuel and the secondary fuel for propulsion and/or to generate electricity to power onboard systems. Advantageously, the primary fuel is recyclable metallic fuel which does not contribute to greenhouse gases when combusted, and so harmful emissions from the hybrid system are greatly reduced in comparison to a conventional system/heat engine that burns solely hydrocarbons. A further advantage is that heat from combustion of the metallic fuel may be sufficient to ignite combustion of the secondary fuel, without further energy input.

[0110] The systems **400**, **420** may also be integrated with conventional power and propulsion systems in gas, hybrid and electric vehicles. According to an embodiment, the heat engine **402** may be coupled to an electric motor and a battery in a hybrid or electric vehicle, whereby the excess (or waste) heat from the heat engine **402** is used to generate electricity stored in the battery. In another embodiment, the heat engine **402** may be coupled to a conventional gas turbine engine for propulsion and power generation. In yet another embodiment, the heat engine **402** may be coupled to a gas turbine and a battery, whereby excess heat from the engine(s) is used to generate electricity stored in the battery. Furthermore, regenerative braking may be included to help with energy recovery.

[0111] The systems **400**, **420** may also be adapted for use in a vehicle to provide a mobile power generator for on-demand power to buildings when a local power grid is down. In such a configuration, the metallic fuel may be combusted in the heat engine **402** when power is needed on demand, and the fuel byproducts may be recycled back into metallic fuel, when power is not needed.

[0112] Referring to FIG. **12**, shown therein is a diagram of a recyclable fuel powered space-to-earth wireless power and data transmission system **820**, according to an embodiment. The system **820** includes one or more satellites **811** in orbit. The satellites **811** include a heat engine to combust metallic fuel for propulsion and to generate electricity to power onboard systems.

[0113] The satellites **811** include transmitters to beam EM radiation **816** down toward the earth from the power generated by the solar cells. The system **820** includes one or more aerial craft **812** positioned or tethered at an intermediate altitude. The aerial craft **812** include arrays of EM radiation transmitters and receivers (including rectennas). The aerial craft **812** receive the radiation **816** beamed down from the satellite **811** and retransmit the radiation **816** downward toward the earth. The system **820** includes ground-based parabolic receivers **815** to collect the EM radiation **816** beamed down from the aerial craft **812**. The parabolic receivers **815** may include rectenna arrays to convert the received radiation **816** to electricity for use on the ground.

[0114] Referring to FIGS. **13**A and **13**B, shown therein are diagrams of a point-to-point payload transfer system **500**, according to an embodiment. The system **500** may be used to transport a payload **502** from the ground to orbit (FIG. **13**A) or launch a spacecraft **504** into orbit (FIG. **13**B). The system **250** includes an array of ground transmitters **506** for beaming up electromagnetic radiation (wireless power). The system **500** includes a launch balloon **508** for carrying the payload **502** or spacecraft **504**.

[0115] The launch balloon **508**, includes a heat engine to combust metallic fuel for propulsion and to generate electricity to power onboard systems. The launch balloon **508** may also be covered in rectennas to receive the radiation beamed up from the ground transmitters **506** and/or solar radiation to provide the launch balloon **508** with energy for propulsion and lift to carry the payload **502**/spacecraft **504**. The launch balloon **508** may transport the payload **502**/spacecraft **504** up to an altitude of approximately **50** km above the earth. The system **500** includes a secondary airship **510**. The secondary airship **510** may track flight path of the launch balloon **508**, deployment of payloads **502**, **504** and/or interface with satellites in orbit.

[0116] Referring to FIG. **13**B, the spacecraft **504** may include a heat exchanger (i.e., thermal rectennas) that can use directed power/radiation, from, for example, the secondary airship **510**, for power and propulsion once separated from the launch balloon **508**.
[0117] Referring to FIG. **14**A, shown therein is a diagram of a cycler transport system **900** between two or more planetary bodies. Conventional space propulsion systems typically only enable one-way travel to distant astronomical bodies due to depletion of fuel reserves carried onboard. Using the systems and methods disclosed herein may advantageously facilitate cycler transport along a figure eight trajectory between two or more planetary bodies by recycling metallic fuel onboard, thereby conserving onboard fuel reserves. Thus, a cycler transport system using recycled metallic fuel may extend a one-way trip into a return trip. Generally, cycler transport by recycling fuel may be possible between any two or more astronomical bodies as shown in FIG. **14**B. Spacecraft may also land on an astronomical body to “refuel” by harvesting regolith for processing into metallic fuel to extend a trip, rather than having to return to Earth for refueling. Cycler transport may also be used with terrestrial vehicles to move between two or more points.
[0118] Further efficiencies in fuel conservation may be achieved by implementing “looping” methods. In a looping method, a vehicle's heat engine is combined (or operably connected) with a thermal power plant to operate in two phases—a propulsion phase and a power phase. During the propulsion phase metallic fuel (e.g., thermites) are ignited, combusted, and expelled from the heat engine to provide propulsion. By leveraging dispersion techniques which utilize the balance between the concentration of the particles in the carrier fluid and the concentration of the heat and energy required for ignition, a variable fraction of the metallic fuel can be combusted in a loop, and the unburnt fuel that is heated by the combustion is captured to inductively generate electricity in the thermal power plant during the power phase. The unburnt fuel is then cycled back to the heat engine for combustion in the next propulsion phase.
[0119] The degree of combustion during the propulsion phase may be controlled by volumetric heating of the metallic fuel to optimize the looping method for propulsion vs. power generation for a given “loop” of metallic fuel usage. For example, when rapid propulsion is required, a first loop will produce complete combustion (no unburn fuel left to be captured), and a second loop will also produce complete combustion. By contrast when both propulsion and power generation is required, a first loop will result in complete combustion and a second loop will result in less than complete combustion whereby the unburnt fuel is captured by a sintering process to generate power thought induction. When only power generation is required (without propulsion) the fuel may be inductively heated by sintering to generate power in the thermal power plant.
[0120] According to various embodiments, other looping processes may include the utilization of nanothermites to generate power and propulsion, and the products harvested for use to drive other processes and reactions such as to create other byproducts, further reduced metal oxides to synthesize metallic fuels, further oxidize metal fuels for power and propulsion generation, and recycle, and reuse the byproducts.
[0121] FIG. **15** is a diagram of a point-to-point (P2P) beam riding system **110**, according to an embodiment. The P2P beam riding system **110** includes at least a pair of craft **112***a*, **112***b* (a second pair of craft **112***c*, **112***d* is also shown). The craft **112***a*, **112***b*, **112***c*, **112***d* may be autonomous or semi-autonomous airships (as shown), balloons or drones (i.e., unmanned aerial vehicles, UAVs). Each craft **112***a*, **112***b*, **112***c*, **112***d* includes at least one transmitter **113** and at least one receiver **114** for transmitting and receiving, respectively, EM radiation, for example, microwave radiation. The craft **112***a*, **112***b*, **112***c*, **112***d* are positioned (in the air) in pairs such that the EM radiation transmitted by a first craft **112***a*, **112***c* is received by a second craft **112***b*, **112***d*.
[0122] The radiation transmitted and received between the craft produces a beam riding “highway” (shaded regions indicated by reference numbers **115***a*, **115***b*), or a microwave tunnel in the case of microwave radiation, in a volume of air between the craft. The beam riding highway **115***a*, **115***b* may be utilized for wireless power transfer (WPT), wireless data transfer between the craft **112***a*,

112*b* as well as providing over-the-air charging, command and control functions, for beam riding aerial craft (e.g., drone **116**) that can be powered and/or recharged by microwave radiation.

[0123] Each beam riding highway **115***a*, **115***b* is directional, that is the direction of radiation transmitted between the craft **112***a*, **122***b* is in one direction. The direction of radiation transmission between the craft **112***a*, **112***b* may be reversed. Consequently, the drone **116**, may only "ride" the beam riding highway **115***a*, **115***b* in the direction of radiation transmission. A shown, the direction of radiation transmission in the first beam riding highway **115***a*, and the direction of travel for the drone **116** within the first beam highway **115***a* is generally in the direction from craft **112***a* to craft **112***b*. The direction of radiation transmission in the second beam riding highway **115***b*, and the direction of travel for the drone **116** within the second beam highway **115***b* is generally in the direction from craft **112***c* to **112***d*. For example, the drone **116** may enter the first beam riding highway **115***a* in the vicinity of the craft **112***a* and ride the first beam riding highway **115***a* between the craft **112***a*, **112***b*, then exit the first beam riding highway **115***a* in the vicinity of craft **112***b*.

[0124] FIG. **16** is a diagram of a system **120** for point-to-point wireless power transmission for wildlife management applications. The system **120** is substantially similar to the system **110** in FIG. **15**, and includes a pair of aerial craft **112***a*, **112***b* that produce a microwave beam riding highway **115***a* between them. The drone **116** includes a rectenna rechargeable power source **118**. The power source **118** may be recharged by the drone **116** entering the beam riding highway **115***a* so that the rectenna receives microwave radiation and converts it to electricity that is stored in the power source **118**.

[0125] In the exemplary application shown in FIG. **16** the drone **116** is used for wildlife management applications in the vicinity of an area of interest, such as an airport to keep birds away from aircraft flight paths. When the drone **116** is low on power, it may fly into the beam riding highway **115***a*, for example, at point A to recharge the power source **118**. As the drone **116** travels between the aerial craft **112***a*, **112***b* along the beam riding highway **115***a*, the power source **118** is recharged. When the power source **118** is sufficiently charged, the drone **116** exits the beam riding highway **115***a*, for example, at point B and may then return to its operational mode of keeping birds away.

[0126] As noted above, the travel of the drone **116** along the beam riding highway is in one direction only (the same direction of microwave radiation transmission between the aerial craft **112***a*, **112***b*) to allow the drone **116** maximum exposure to microwave radiation in order to charge the power source to sufficient levels required for operation. The drone **116** may travel a further distance along the beam riding highway **115***a* to recharge the power source **118** more.

[0127] Referring to FIG. **17**, one or more beam riding highways **115** may be implemented within a point-to-point beam riding system **125** to allow for bidirectional or multi-directional travel of a beam riding drone **116**. Accordingly, the drone **116** may ride one beam riding highway **115** to travel in one direction and ride another beam riding highway **115** to travel in another direction. Generally, a beam riding highway **115** may be implemented to travel in any direction between appropriately positioned aerial craft **112**. The direction of travel of the drone **116** along the beam riding highways **115** may result in a change altitude, a change in position at the same altitude or a change in altitude and position of the drone **116**.

[0128] FIG. **18** is a diagram of inductive-coupled magnetic resonance wireless power transfer **130** between a transmitting aerial craft **131** and a receiving aerial craft **132**. The transmitting craft **131** includes a power source **133** connected to an oscillator **134**. The receiving craft **132** includes a resonant circuit **135** connected to a rectifier **136**. The oscillator **134** draws DC power from the power source **133** and converts it to AC power in a circuit to generate a magnetic field, B. If the receiving craft **132** is in close enough proximity to the transmitting craft **131**, the resonant circuit **135** will be within the magnetic field, B, thus causing a current flow through the resonant circuit **135**. The AC current flowing from the resonant circuit **135** is converted to DC power by the rectifier **136** and can then be used to power the load of the receiving craft **132**.

[0129] Referring to FIGS. **19-20**, shown therein are diagrams of an inductive power transfer system **140** and a resonant power transfer system **150**, **155** for wireless power transmission between aerial craft.

[0130] The inductive power transfer system **140** includes a transmitting aerial craft **142** having a primary (transmitter) coil and a receiving aerial craft **146** having a secondary (receiver) coil. It should be noted that the primary and secondary coils are located within the respective craft **142**, **146** and are depicted as primary coil field **144**, and secondary coil field **148** for ease of explanation. Current running passing through the primary coil generates a magnetic field B in the proximity of the primary coil field **144**. If the receiving craft **144** is in proximity to the magnetic field such that a sufficient portion of the magnetic field intersects the secondary coil, a current will be generated in the secondary coil thus resulting in inductive power transfer between the transmitting craft **142** and the receiving craft **146**.

[0131] The resonant power transfer systems **150**, **155** includes a transmitting aerial craft **151** having a primary (transmitter) coil and one or more receiving aerial craft **152***a*, **152***b*, **152***c*, **152***d*, **152***e* each having a secondary (receiving) coil. It should be noted that the primary and secondary coils are located within the respective craft **151**, **152***a*, **152***b*, **152***c*, **152***d*, **152***e* and are depicted as a primary coil field **153**, and secondary coil fields **154***a*, **154***b*, **154***c*, **154***d*, **154***e* for ease of explanation. In the resonant power transfer systems **150**, **155**, the wireless transmission of power from the transmitting craft **151** to the receiving craft **152***a*, **152***b*, **152***c*, **152***d*, **152***e* depends only on the secondary coils **154***a*, **154***b*, **154***c*, **154***d*, **154***e* intersecting a reasonable amount of primary coil flux lines (i.e., intersection the magnetic field, B, generated by current passing through the primary coil **153**).

[0132] A resonant power transfer system **155** may be preferable to the inductive power transfer system **140** depending on the size and number of the respective transmitting and receiving craft. For example, in the resonant power transfer system **155** more smaller sized craft may receive wireless power transmission simultaneously compared to the inductive power transfer system **140**.

[0133] FIG. **21** is a diagram of a hybrid wireless power transmission system **160**, according to an embodiment. The hybrid power transmission system **160** may include one or more of inductive power transfer systems **161** (i.e., inductive power transfer system **140** in FIGS. **19-20**), resonant power transfer systems **162** (i.e., resonant power transfer systems **150**, **155** in FIGS. **19-20**) and beam riding highways **163** (i.e., beam riding highway **115***a*, **115***b* in FIGS. **15-17**) between respective transmitting and receiving craft.

[0134] The hybrid wireless power transmission system **160** may further include a plurality of ground parabolic transmitters **164** to transmit EM radiation from the ground that is received by aerial craft **166** having rectennas to convert the EM radiation to current and wirelessly transmit the power to other aerial craft via one or more inductive power transfer systems **161**, resonant power transfer systems **162** and/or beam riding highways **163**.

[0135] In addition, the transmitting craft **167** and the receiving craft **168** may include lasers **169** to transfer excess or unused EM radiation received by the receiving craft **168** back to the transmitting craft **167** as laser radiation to conserve energy and propagate the beam riding highway **163** for use by other aerial craft. The craft **167**, **168** may further include one or more transmitters and receivers (not shown) for transmitting control and data signals between the craft **167**, **168**.

[0136] Accordingly, the hybrid power transmission system **160** may be readily adapted, as needed, to power a variety of aerial craft having different wireless energy transfer capabilities and to also provide control and data signals to perform a variety of tasks.

[0137] FIG. **22** shows diagrams of system architectures **170**, **171**, **172** for wireless power and control data transmission, according to several embodiments. The control data may be: data signals to control operation or the aerial craft; data signals with respect to power usage/transmission; sensor data, advanced metering interfaces, wayfind, and/or in-situ monitoring data etc. Each of the power receiver and power transmitter units depicted in the architectures **170**, **171**, **172** may be located on an aerial craft that is part of a larger deployment or swarm of aerial craft.

[0138] A central system architecture **170** includes a central transmitter unit surrounded by receiver units. Power is wirelessly transmitted one-way from the central transmitter unit to each of the receiver units. Control (data) signals may be wirelessly transmitted two-way between the central unit and any of the receiver units.

[0139] A distributed system architecture **171** includes a central power transmitter unit, a power transmitter/receiver unit and several receiver units surrounding the central transmitter unit. The central transmitter unit transmits power to each of the surround receiver units including the transmitter/receiver unit. The transmitter/receiver unit may also transmit power to adjacent receiver units. Control (data) signals may be wirelessly transmitted two-way between the central transmitter unit and any of the receiver units as well as between the transmitter/receiver unit and adjacent receiver units.

[0140] A hybrid system architecture **172** includes a central power transmitter/receiver unit surrounded by several receiver units, a power transmitter unit and a second power transmitter/receiver unit. The central transmitter/receiver unit may transmit power to any of the surrounding receiving units. The power transmitter unit may transfer power only to the adjacent receiving unit and central transmitter/receiver unit. Similarly, the second power transmitter/receiver unit may only transmit power to the adjacent receiving unit and the central transmitter/receiver unit. Control signals may be wirelessly transmitted two-way between the central transmitter/receiver unit and any of the surrounding receiver units, the power transmitter unit and the second transmitter/receiver unit, as well as between the transmitter/receiver unit and adjacent receiver units.

[0141] FIG. **23** is a diagram recording wireless power and data transfer in a blockchain **180**, according to an embodiment. Each wireless power transmission (light shaded arrows) and control (data) signals (dark shaded arrows) transmitted and received between two aerial craft **182**, **184** may be recorded as a transaction between the transmitting and receiving craft using blockchain technology between mobile nodes.

[0142] FIGS. **24-25** are diagrams of a microwave elevator system **200** for orbital raising/descending and horizontal/vertical travel, according to an embodiment. It should be noted that the diagrams are not drawn to scale. The elevator system **200** includes a first multilayer rectenna structure **202** joining a first pair of aerial craft in a dumbbell configuration at approximately **30** km altitude above the earth. The first multilayer rectenna structure **202** includes a microwave transmitter/pilot signal receiver layer. The elevator system **200** includes a second multilayer rectenna structure **204** joining a second pair of aerial craft in a dumbbell configuration at approximately **50** km altitude above the earth. The second multilayer rectenna structure **204** includes a solar cell layer attached to a microwave transmitter/pilot signal receiver layer. The elevator system **200** may include a tether **206** for physically connecting the first multilayer rectenna structure **202** to the second multilayer rectenna structure **204**.

[0143] The system **200** includes ground parabolic microwave transmitters **208** for transmitting microwave radiation upward to the first rectenna structure **202**. The radiation received by the first rectenna structure **202** may be retransmitted and received by the second multilayer rectenna structure **204**, thus forming a beam riding highway between the first and second multilayer rectenna structures **202**, **204**. Similarly, solar radiation absorbed by the second multilayer rectenna structure **204** may be transmitted downward as microwave radiation that is received by the first rectenna structure **202** thus forming a beam riding highway between the first and second multilayer rectenna structures **202**, **204**. Aerial craft **203** having rectennas may enter the beam riding highway for vertical (up/down) travel between the first and second multilayer rectenna structures **202**, **204**.

[0144] The tether **206** may further include a microwave transmitter array to project a horizontal beam riding highway which aerial craft **203** may enter for horizontal travel between the first and second multilayer rectenna structures **202**, **204**.

[0145] FIG. **26** is diagram of module swapping system **210** for aerial craft, according to an embodiment. The module swapping system **210** may be used to swap modules between aerial craft. The module may be a fuel source (e.g., a battery, capacitors, super capacitors, inductors, super inductors, metallic fuel, reactive metal compounds, or the like). The module may also be structures of rectennas, coils, capacitors or solar cells to receive EM radiation. The module may be electronics, on-board computers, sensors or data storage devices or other parts for repair and/or maintenance, reconfiguration and/or component upgrade.

[0146] The module swapping system **210** may be positioned within a “mothership” or large aerial craft configured to service smaller aerial craft. The module swapping system **210** includes a landing pad **211** for receiving aerial craft for module swapping. The landing pad **211** may be present in a hanger, or the like, on the mothership. The landing pad **211** may be located on an external surface of the mothership.

[0147] The module swapping system **210** includes one or more drums **212** for storing modules. Generally, one module is stored within one drum **212**. The drums **212** may be stored in a storage configuration adjacent to the landing pad **211** such that when a drum **212** is to be swapped, it is rotated from the storage position onto the landing pad **211** for swapping. The module swapping system **210** includes servos **213** connected to each drum **212** for rotating the drums **212** from the storage configuration to a swapping position on the landing pad **211**. The servos **213** may also swap the module within the drum **212** for the module on the aerial craft on the landing pad **211**. The module swapping system **210** further includes a controller **214** for controlling the servos **213** and swapping of modules. The controller **214** may operate to swap modules according to a schedule with autonomous and semi-autonomous operations.

[0148] FIG. **27** is a diagram of an in-flight charging system **270** for drones, according to an embodiment. The system **270** includes motherships **271** (i.e., airships) to transport, deploy and recharge drones **272**. The mothership **271** includes a drone deployer **273** to store and deploy fully charged drones **272***a*. The mothership **271** includes a battery swapping system **274** for recharging battery depleted (uncharged) drones **272***b*. Uncharged drones **272***b* may dock with the mothership **271** to have their battery replaced by the battery swapping system **274**. Uncharged drones **272***b* may also dock with the mothership **271** to have their battery recharged. The mothership **271** may also include components (inductions coils, etc.) for wireless power transfer between the mothership **271** and uncharged drones **272***b* so that drones may recharge in-flight when in close enough proximity to the mothership **271**.

[0149] FIG. **28** is a diagram of ground tethered hybrid wireless power transfer systems **300**, **301**, **302**, **303**, **304**, according to several embodiments. Each system **300**, **301**, **302**, **303**, **304** includes a tethered airship **305** covered in rectennas **306**. Each system **300**, **301**, **302**, **303**, **304** includes a ground-based power supply **307**, **308**, **309**, **310**. The ground-based power supply may be a vehicle **307**. The ground-based power supply may be a radio communications tower **308**. The ground-based power supply may be an utility pole **309**. The ground-based power supply may be a building/structure **310**. Power from the ground-based power supply **307**, **308**, **309**, **310** is sent up to the airships **305** via the tether.

[0150] FIG. **29** is a diagram of ground tethered hybrid wireless power transfer system **300** shown in relation to untethered rectenna covered airships **311**.

[0151] Referring to FIGS. **28** and **29**, transmitting power from a ground-based source to an untethered airship **311** requires a high intensity of electromagnetic radiation. Such a high intensity beam of radiation may cause interference with electrical devices on or near the ground. Accordingly, it may be advantageous to transmit power from a ground-based power source to a tethered airship **305**, via a tether, to eliminate the potential for electromagnetic radiation interference near the ground. Once the power is received by the tethered airship **305**, it may be beamed as radiation to other airships at higher or lower elevations without interfering with ground-based electrical devices.

[0152] FIG. **30** is a diagram of an air-water system **315** for wireless power transmission, according to an embodiment. The system **315** includes an airship **316** having a transmitter to beam radiation downward. The system **315** includes a buoy **317** having rectennas **318** for receiving the radiation beamed from the airship **316** to create a beam riding highway **319** between the airship **316** and the buoy **317**. The beam riding highway **319** may be used to transport drones **320** between the airship **316** and the buoy **317** in the manner described above with reference to FIGS. **2-4**. Radiation in the beam may also be received by the rectennas **318** on the buoy **317** and converted to electricity. The buoy **317** may include solar cells for converting solar radiation to electricity. The solar cells and rectennas **318** on the buoy **317** may be deployable, inflatable and additively manufactured.
[0153] The buoy **317** may be configured as a charging station to store power generated by the solar cells and/or the rectennas. The buoy **317** may include underwater architecture (not shown) to support the charging of multiple underwater vehicles **321**.
[0154] FIG. **31** is a diagram of aerial craft connectivity with smart city infrastructure for wireless power and data transmission, according to an embodiment. Aerial craft **330** having a phased array communication system can be used to create a mobile backhaul support system for rapid response communication with mobile phones, computers and devices on the ground (not shown) by connecting to existing communication infrastructure **335** (e.g., utility poles). Aerial craft **330** may also connect with existing electrical grid infrastructure **336** (e.g., utility poles) to draw power for recharging, rather than having to land to recharge and expend additional battery power unnecessarily. The aerial craft **330** may also transmit power to the grid **336**.
[0155] While the above description provides examples of one or more apparatus, methods, or systems, it will be appreciated that other apparatus, methods, or systems may be within the scope of the claims as interpreted by one of skill in the art.

Claims

1. A method for producing electricity and propulsion from recyclable metallic fuels, comprising: inductively heating a metallic fuel in a heat engine, causing at least partial combustion of the metallic fuel; transferring heat from the at least partial combustion of the metallic fuel to release energy; and using the released energy to drive propulsion of a vehicle.
2. The method of claim 1, wherein the metallic fuel is one or more of: a nanothermite, a microthermite and thermite.
3. The method of claim 1, wherein the metallic fuel comprises a metal and an oxidizer.
4. The method of claim 3, wherein the oxidizer is a second metal oxide.
5. The method of claim 1, further comprising using steam to drive an electrical generator to produce electricity.
6. The method of claim 1, further comprising passively capturing and converting excess heat from the at least partial combustion of the metallic fuel into electricity by a thermal energy harvesting system.
7. The method of claim 1, further comprising: capturing fuel products and unburnt fuel from incomplete combustion of the metallic fuel, wherein the fuel products include a first metal oxide; directing the unburnt metallic fuel and the fuel products to storage and/or to the heat engine for further combustion; and recycling the first metal oxide to regenerate the metallic fuel and/or other products.
8. The method of claim 7, wherein the fuel products further include a metal that is oxidizable for heating and/or combustion.
9. The method of claim 7, further comprising: inductively generating electricity in a thermal energy harvesting system using heat from the unburnt metallic fuel and the fuel products.
10. The method of claim 7, further comprising: recycling the fuel products by one or more chemical processes to produce the other products.

11. The method of claim 10, wherein the one or more chemical processes comprise one or more of: hydrogenation, methanation, carbothermal reduction and electrolysis or the like.
12. The method of claim 1, wherein the metallic fuel is heterogeneous comprising metallic particulates surrounded by a binder.
13. The method of claim 12, wherein the binder is a nanocomposite hydrogel.
14. The method of claim 1, wherein the metallic fuel is heterogeneous comprising metallic particles and a catalyst for catalytic oxidation of the metallic particles or catalytic reduction of the fuel byproducts.
15. The method of claim 14, wherein the catalyst is stimuli-responsive being chemically, mechanically, magnetically or thermally activatable.
16. The method of claim 10, wherein energy for the one or more chemical processes is provided by inductive-coupled and/or magnetic resonance wireless energy transmission.
17. The method of claim 1, further comprising synthesizing the metallic fuel from a plurality of fuel sources harvested from the Earth, Moon, Mars, other planets, asteroids, planetoids, other celestial bodies, or a combination thereof.
18. The method of claim 1, further comprising controlling volumetric heating of the metallic fuel to regulate combustion.
19. The method of claim 1, wherein the vehicle is one of: a land vehicle, an aerial vehicle and a water vehicle.
20. A vehicle configured to use a recyclable metallic fuel for propulsion, comprising: a fuel tank for storing the metallic fuel; a working fluid source; a mixing tank, for mixing the metallic fuel and working fluid to form a slurry; a heat engine having an induction heating assembly, wherein the slurry is inductively heated in the heat engine causing at least partial combustion of the metallic fuel; a closed loop heat transfer system for transferring heat from the at least partial combustion of the metallic fuel to generate steam; and a propulsion system connected to the heat transfer system, wherein the propulsion system is driven by the steam to move the vehicle.
21. The vehicle of claim 18, further comprising an electrical generator driven by the working fluid to produce electricity for powering onboard systems.
22. The vehicle of claim 18, further comprising a thermal energy harvesting system connected to the heat engine to capture and convert excess thermal energy from the at least partial combustion of the metallic fuel into electricity.
23. The vehicle of claim 18, further comprising: at least one combustion chamber for combusting the metallic fuel; at least one reaction chamber for generating thermal power using heat from unburnt metallic fuel and fuel products; at least one storage system for capturing the unburnt metallic fuel and the fuel products; and at least one recycling system for directing the captured unburnt metallic fuel and/or the fuel products to the at least one combustion chamber and/or the at least one reaction chamber.
24. The vehicle of claim 21, further comprises one or more storage tanks for storing the unburnt metallic fuel and the fuel products.
25. The vehicle of claim 21, further comprising a second fuel recycling system comprising: a second reaction chamber for reducing the fuel byproducts by one or more reductive processes to regenerate the metallic fuel; and a second recycling system for directing the fuel byproducts from the at least one storage system to the second reaction chamber.
26. The vehicle of claim 18, further comprising one or more of: rectennas and solar panels, for receiving energy wirelessly, wherein the energy is used to power the induction heating assembly.
27. The vehicle of claim 18, further comprising a plurality of magnetic induction coils.
28. The vehicle of claim 18, further comprises a temperature regulating system for controlling the volumetric heating of the metallic fuel in the heat engine.
29. The vehicle of claim 18, further comprising a secondary fuel tank for storing a secondary fuel, wherein the secondary fuel is combusted with the metallic fuel in the heat engine.

30. The vehicle of claim 27, wherein the secondary fuel is a hydrocarbon.
31. The vehicle of claim 18, wherein the vehicle is one of: a land vehicle, an aerial vehicle, a water vehicle and a spacecraft.