



Recyclable metal fuels for clean and compact zero-carbon power



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ABSTRACT

Metal fuels, as recyclable carriers of clean energy, are promising alternatives to fossil fuels in a future low-carbon economy. Fossil fuels are a convenient and widely-available source of stored solar energy that have enabled our modern society; however, fossil-fuel production cannot perpetually keep up with increasing energy demand, while carbon dioxide emissions from fossil-fuel combustion cause climate change. Low-carbon energy carriers, with high energy density, are needed to replace the multiple indispensable roles of fossil fuels, including for electrical and thermal power generation, for powering transportation fleets, and for global energy trade. Metals have high energy densities and metals are, therefore, fuels within many batteries, energetic materials, and propellants. Metal fuels can be burned with air or reacted with water to release their chemical energy at a range of power-generation scales. The metal-oxide combustion products are solids that can be captured and then be recycled using zero-carbon electrolysis processes powered by clean energy, enabling metals to be used as recyclable zero-carbon solar fuels or electrofuels. A key technological barrier to the increased use of metal fuels is the current lack of clean and efficient combustor/reactor/engine technologies to convert the chemical energy in metal fuels into motive or electrical power (energy). This paper overviews the concept of low-carbon metal fuels and summarizes the current state of our knowledge regarding the reaction of metal fuels with water, to produce hot hydrogen on demand, and the combustion of metal fuels with air in laminar and turbulent flames. Many important questions regarding metal-fuel combustion processes remain unanswered, as do questions concerning the energy-cycle efficiency and life-cycle environmental impacts and economics of metals as recyclable fuels. Metal fuels can be an important technology option within a future low-carbon society and deserve focused attention to address these open questions.

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Contents

1. Energy and climate problems and solutions	170
1.1. Climate change and fossil energy resources.....	170
1.2. Bioenergy and biofuels	171
1.3. Solar energy resources.....	171
1.4. Advanced nuclear.....	171
2. Need for energy storage and tradeable energy commodities.....	171
2.1. Electricity and mechanical-energy storage.....	172
2.2. Cryogenics and thermal-energy storage	172
2.3. Need for chemical energy carriers.....	172
2.4. Chemical-energy storage in batteries.....	172
2.5. Solar fuels and electrofuels	172
2.5.1. Economics of electrofuels.....	173
2.6. Hydrogen as an electrofuel	173
2.6.1. Energy-cycle efficiency of hydrogen systems.....	173
2.6.2. Problems with hydrogen storage and safety.....	173
2.7. Synthetic hydrocarbon solar fuels and electrofuels.....	174

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3.	Metals as zero-carbon, recyclable electrofuels	174
3.1.	Metals as fuel additives in propellants and energetic materials.....	174
3.2.	Metals as fuels within batteries.....	175
3.3.	Metals as recyclable electrofuels	175
3.4.	Metal fuel options	176
3.5.	Recycling of the metal-oxide products	176
3.5.1.	MAGIC Cycle.....	176
3.5.2.	Open-loop chemical looping	176
3.5.3.	Reduction of iron with hydrogen.....	176
3.5.4.	Metal production using electrolysis	176
3.6.	Energy-cycle efficiency of metal fuels	176
4.	Harnessing power from recyclable metal fuels.....	177
5.	Wet Cycle: metal-water reaction to produce hydrogen	177
5.1.	Low-temperature aluminum-water reactions	178
5.2.	Increasing the rate of low temperature metal-water reactions	178
5.2.1.	Use of alkaline solutions or direct metal-water contact	178
5.2.2.	Nanoparticles	178
5.2.3.	Alloys, galvanic reactions, and catalysts	179
5.2.4.	Problems with the low-temperature Wet Cycle.....	180
5.3.	High-temperature reactions to increase rates and yields.....	180
5.3.1.	Reaction yield and penetration thickness	180
5.3.2.	Ultrasonic agitation to increase rates and yields.....	181
5.4.	Metal-water combustion.....	181
5.4.1.	Metal-water combustion for underwater propulsion.....	181
5.4.2.	Metal-water combustion for rocket propulsion.....	181
5.4.3.	Metal-water combustion rates	181
5.4.4.	Storage and handling of aluminum-water propellants	181
5.4.5.	Efficiency of aluminum-water combustion	182
5.4.6.	Hydrogen peroxide accelerates metal-water combustion	182
5.4.7.	Metal-water combustion for air-breathing propulsion.....	182
5.4.8.	Metal-water combustion for compact power systems.....	183
5.5.	Engines and fuel cells fuelled by hot hydrogen	183
6.	Dry Cycle: direct metal-air combustion.....	183
6.1.	Metal-particle combustion in internal-combustion engines.....	184
6.2.	Metal-fuelled combustor and applications	184
6.2.1.	Industrial and residential heating.....	184
6.2.2.	Stationary power generation.....	185
6.2.3.	External-combustion engines for motive power.....	185
6.3.	Stabilized combustion of metal fuels for heat and power	185
6.3.1.	Stabilized metal flames.....	186
6.3.2.	Metal-particle ignition and combustion regimes	186
6.3.3.	Metal flame modeling	187
6.3.4.	Enhancing combustion rate of metal-fuelled combustors	187
6.3.5.	Emissions from metal flames	188
6.3.6.	Collecting solid metal-oxide products	188
7.	Intense power generation from metal fuels.....	188
7.1.	Power density of fuel cells, batteries, and engines	188
7.2.	Energy and power densities of different clean energy systems	188
8.	Outlook and future research directions	189

1. Energy and climate problems and solutions

Multiple indicators of quality of life, from reduced childhood malnutrition to increased gender equality [1], correlate directly with how much energy is harnessed by a society per person, as well as how efficient that society is in converting that energy into useful products and services that improve living conditions [1–6]. Energy is needed to produce and transport all raw materials and manufactured goods, to provide all services, and underpins all economic activity and wealth creation [5]. The average citizen of a (energy) rich country takes advantage of around 80 times more energy than is produced by their own metabolisms, a feat enabled by our access to fossil fuels [5].

The global economy is currently driven by the international production, trade, and consumption of fossil fuels because they: are relatively cheap and have been readily available, are energy dense, can be burned in internal-combustion engines at high power densities,

and are easily transportable and relatively safe to handle. The impressive energy density of fossil fuels can be appreciated by considering the fact that a teaspoonful of hydrocarbon fuel contains chemical energy, when burned with air, equal to the kinetic energy of a 1000 kg automobile travelling at 100 km/hr [7].

1.1. Climate change and fossil energy resources

Unfortunately, combustion of fossil hydrocarbon fuels produces carbon dioxide emissions that cause climate change [8–10]. Limiting anthropogenic global warming to 2 °C requires limiting consumption of fossil energy sources, which would also limit our future economic growth [8,11], leaving a gap that must be filled through development of renewable energy sources [10].

Meanwhile, we may have already passed the peak in conventional crude oil production, or Peak Oil [4,12,13], and may soon be

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