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Direct combustion of recyclable metal fuels for zero-carbon heat and power

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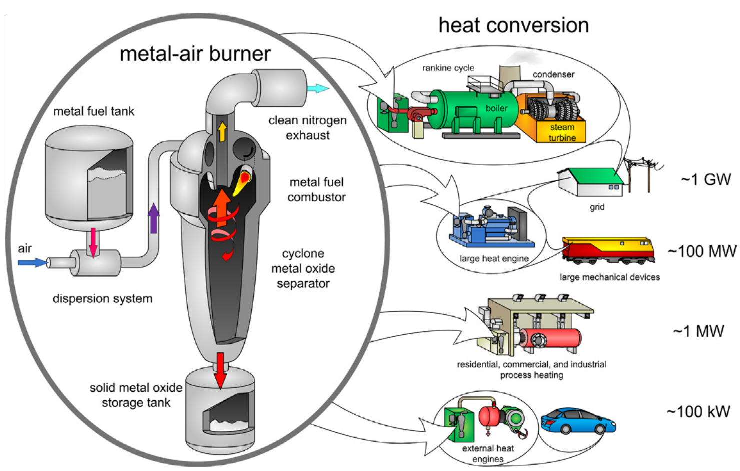
HIGHLIGHTS

- Metals are promising high-energy density, low-emission, recyclable energy carriers.
- Metal fuels can be burned with air to produce heat for many applications.
- A novel combustor that can burn metal fuels is proposed.
- Metal-oxide combustion products can be captured and recycled.
- Use of clean power sources to recycle metals enables low-net-carbon emissions.

GRAPHICAL ABSTRACT

Concept drawing of a metal-fuelled combustor and its possible applications at a range of power-generation scales.



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ABSTRACT

It is becoming widely recognized that our society must transition to low-carbon energy systems to combat global climate change, and renewable energy sources are needed to provide energy security in a world with limited fossil-fuel resources. While many clean power-generation solutions have been proposed and are being developed, our ability to transition to a low-carbon society is prevented by the present lack of clean and renewable energy carriers that can replace the crucial roles that fossil fuels play, due to their abundance, convenience and performance, in global energy trade and transportation. Any future low-carbon energy carriers that aim to displace or supplement fossil fuels must have high energy densities for convenient trade and storage, and should be consumable within efficient high-power-density engines for transportation, heavy machinery, and other off-grid energy applications.

Hydrogen and batteries have been widely studied but they are not suitable for use as international energy-trading commodities and they cannot provide the energy density and safety demanded by society. Metal fuels, produced using low-carbon recycling systems powered by clean primary energy, such as solar and wind, promise energy densities that are competitive to fossil fuels with low, or even negative, net carbon dioxide emissions. To date, however, few practical high-power-density end-use devices for generating heat or power from metal fuels have been proposed.

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This paper proposes a novel concept for power generation in which metal fuels are burned with air in a combustor to provide clean, high-grade heat. The metal-fuel combustion heat can be used directly for industrial or residential heating and can also power external-combustion engines, operating on the Rankine or Stirling cycles, or thermo-electric generators over a wide range of power levels. A design concept is proposed for a metal-fuelled combustor that is based upon extensive experimental and theoretical studies of stabilized and propagating metal flames performed at McGill University. This paper also reviews the fundamental and applied aspects of metal-fuel combustion in order to provide the framework needed to assess any potential metal engine technologies. The energy and power densities of the proposed metal-fuelled zero-carbon heat engines are predicted to be close to current fossil-fuelled internal-combustion engines, making them an attractive technology for a future low-carbon society.

1. Introduction

1.1. The need for clean recyclable fuels

To mitigate global climate change, our energy and transportation systems must transition away from fossil-fuel sources to zero-carbon clean and renewable energy sources [1,2]. Alternatives must also be found to offset future constraints on our global economic growth that are associated with finite fossil-fuel reserves [3,4]. Biofuels are one widely-discussed option [5,6], but estimates indicate that bioenergy alone cannot fully displace fossil fuels in a future low-carbon society [1,7–9] due, primarily, to the low effective energy and power densities associated with photosynthesis [7,10]. Harnessing hydro, solar, wind, geothermal and, eventually, clean thermonuclear power [11] can, in principle, completely eliminate fossil fuels from electricity production [7,12,13].

More difficult, however, is to replace the other essential roles of fossil fuels, including their use as energy-trading commodities and transportation fuels. Indeed, even if electricity is produced with clean energy sources it cannot be stored, transported or traded as easily as hydrocarbons. Therefore, clean and renewable energy carriers are needed that can be transported and stored, which would enable the separation of the primary energy production and end-use consumption in both space and time. To date, batteries and hydrogen are the most-commonly proposed energy carriers for a future low-carbon society [1,7,13–15].

High-power-density, internal-combustion engines (ICEs) burning convenient high-energy–density hydrocarbon (fossil) fuels are essential components of modern society that are difficult to replace [16,17]. These combustion engines power everything from automobiles to locomotives and ships to passenger jets. Thus, it is imperative to have a clean energy carrier, and associated power system, that has energy and power densities on par with hydrocarbon fuels and ICEs so that they can be used in a similar manner. To date, the handful of solutions that have been proposed are, in most cases, inferior to hydrocarbon-fuelled ICEs in terms of fuel energy density and engine power density. Society requires more energy carrier options that can provide high energy and power densities for a range of applications that fossil fuels are dominant in today.

1.2. Batteries

In transportation, the fact that batteries have an energy density that is more than an order of magnitude lower than fossil fuels leads to them being barely sufficient for small passenger cars [18], and not at all suitable for high-power vehicles and machinery, such as trucks, construction equipment, military vehicles, locomotives, or ships. The volumetric power density, P/V [kW/m^3], of a power system fuelled by chemical energy can be estimated using dimensional analysis as:

$$\frac{P}{V} \sim \eta q_{\mathrm{m}} \rho_{\mathrm{m}}\, \dot{\omega} \tag{1}$$

where η is the efficiency of the power system, q_{m} [kJ/kg] and ρ_{m} [kg/m^3] are the specific energy and density of the chemical reactants, respectively, and $\dot{\omega}$ [1/s] is the characteristic chemical-reaction rate. Traditional batteries must contain both fuel and oxidizer, reducing the energy density of the fuel system, $q_{\mathrm{m}}\rho_{\mathrm{m}}$ [kJ/m^3]. Furthermore, chemical reactions in batteries proceed at room temperature, resulting in slow reaction rates, $\dot{\omega}$, and low power densities.

In contrast, fossil-fuelled ICEs burn fuels with air at high temperatures leading to high reaction rates and, together with the high pressures that maximize the air–fuel mixture density, produce high power densities. The combustion of fuels with air leads to system energy densities that are much higher than traditional batteries since the air supplies the oxidizer for "free", which is why airplanes are powered by air-breathing gas-turbine (jet) engines instead of rockets.

Indeed, metal–air batteries, using aluminum, zinc, iron or lithium anodes, make use of the oxygen available within air, as well as the high energy density of metals, in order to improve their energy and power densities [18–24]. Unfortunately, the low temperature of the oxygen-reduction reaction at the cathode leads to slow kinetic rates and requires expensive catalysts and large catalyst surface area, as well as the inert catalyst-support matrix and electrolyte, all of which results in the low power densities of available metal–air batteries [18,25]. The requirement for an oxygen-reduction catalyst, and its associated support materials, also limits the power density achievable by fuel cells [18]. In order to maximize performance, the power system must contain a minimum of inert support materials, or *dead weight*, and react or combust fuels with air at high energy-conversion, or heat-release, rates.

1.3. Hydrogen

For the past few decades, hydrogen, produced using clean electrical power, has been widely assumed to be the universal carbon-free energy commodity of the future that will be used for energy storage and transportation [1,14,15]. Hydrogen promises good energetic performance due to its high specific energy, its high reactivity, and its ability to be used in a variety of energy-conversion devices ranging from ICEs and gas-turbine engines to fuel cells, while producing nearly zero pollutant emissions [26–28].

The hydrogen economy, however, has not yet materialized due to two major obstacles that are difficult to overcome: the low density of the compressed hydrogen gas and the inherent fire and explosion hazards associated with hydrogen storage and refueling [15,29]. Even as a cryogenic liquid, the energy density of hydrogen is more than an order of magnitude lower than that of gasoline or other hydrocarbon fuels [30]. Compression and liquefaction of