mixture can generate additional work from the engine and would also extend the flammability limits of the resulting mixture with air, possibly allowing operation of the engine at ultra-fuel-lean conditions to simultaneously improve the efficiency and reduce nitrogen oxide emissions. Many demonstration programs have shown the possibility of developing hydrogen-fueled ICEs that have better efficiency and comparable, if somewhat lower, power density to gasoline engines [19,20]. More research is needed into how to best use the hot, high-pressure hydrogen-steam mixtures, produced from the high-temperature metal-water reactors discussed in this paper, in practical internal-combustion engine technology.

5.5. External-combustion engines fueled by metal-water reactions

Another alternative power system would be the use of an external-combustion heat engine. Such heat engines are used ubiquitously for power generation in nuclear, coal, or biomass fueled power stations [151,152]. Smaller-scale heat engines, based on the Stirling or Rankine cycles, can also be used for transportation or portable-power applications [153–155], at power densities and specific powers comparable to that of internal-combustion engines [153]. An external-combustion heat engine could naturally use both the thermal energy from the aluminum-water reaction and the thermal energy of the hydrogen-air combustion, potentially maximizing the conversion of the available chemical-energy flux into motive power. External-combustion Rankine or Stirling heat engines, or thermo-electric generators, have been proposed for use in underwater propulsion systems, based on the aluminum-water reactor, with projected system efficiencies around 30% [44].

5.6. Power and energy density of metal-fueled systems compared to other clean-energy options

This paper has shown that the high energy density of metal fuels, along with the ability to react them at high conversion rates during high-temperature metal-water combustion, can yield exceptional power densities. The potential performance of heat engines using the metal-water reaction to produce hot hydrogen is estimated and compared to the power and energy densities of other clean-energy systems in Fig. 8 in a Ragone plot.

A Ragone plot compares the tradeoff in specific power, $\mathcal{P}_{m,s}$, vs. energy, $\mathcal{E}_{m,s}$, or power, $\mathcal{P}_{V,s}$, vs. energy, $\mathcal{E}_{V,s}$, density and is commonly used in the battery literature. On a Ragone plot, batteries show a tradeoff between energy and power density, because internal resistance is needed to prevent self-discharge and obtain high energy densities, which directly reduces the maximum discharge current and, hence, power density [156]. See the Supplemental Material for details on how the power and energy densities, and the specific powers and energies, plotted in Fig. 8 are estimated for battery and supercapacitor systems.

For heat engines, a similar tradeoff occurs between specific power and energy for different reasons. A heat engine, or fuel cell system, is essentially an engine, or fuel cell, connected to a fuel tank. The specific energy of the total system, $\mathcal{E}_{m,s}$, is the energy produced by the engine, E_{out}, divided by the total mass of the system, m_s:

$$\mathcal{E}_{m,s} = \frac{E_{out}}{m_s} = \frac{E_{out}}{m_{fuel} + m_{e/fc}} \tag{9}$$

where the mass of the system is the sum of the mass of the fuel carried on board, m_{fuel}, and the mass of the engine or fuel cell, $m_{e/fc}$.

Since the mass and the power of the engine are independent of the size of the fuel tank, the only variable in the system is the range or, equivalently, the time of operation, which is controlled by the amount of fuel available or the mass of the fuel tank. The total energy output of the system, E_{out}, can be expressed as the product of the heat of reaction per mass of the fuel, $\mathcal{E}_{m,f}$, the mass of the fuel, m_{fuel}, and the efficiency of the system, η, or, alternatively, as the product of the engine power, P, and the time, t, over which power is delivered. This allows the mass of the fuel to be expressed as a function of these variables:

$$E_{out} = \eta E_{fuel} \rightarrow Pt = \eta\,\mathcal{E}_{m,f}\,m_{fuel} \rightarrow m_{fuel} = \frac{Pt}{\eta\,\mathcal{E}_{m,f}} \tag{10}$$

The following equation is therefore obtained for the specific energy of a heat-engine or fuel-cell system for different power settings and operation times:

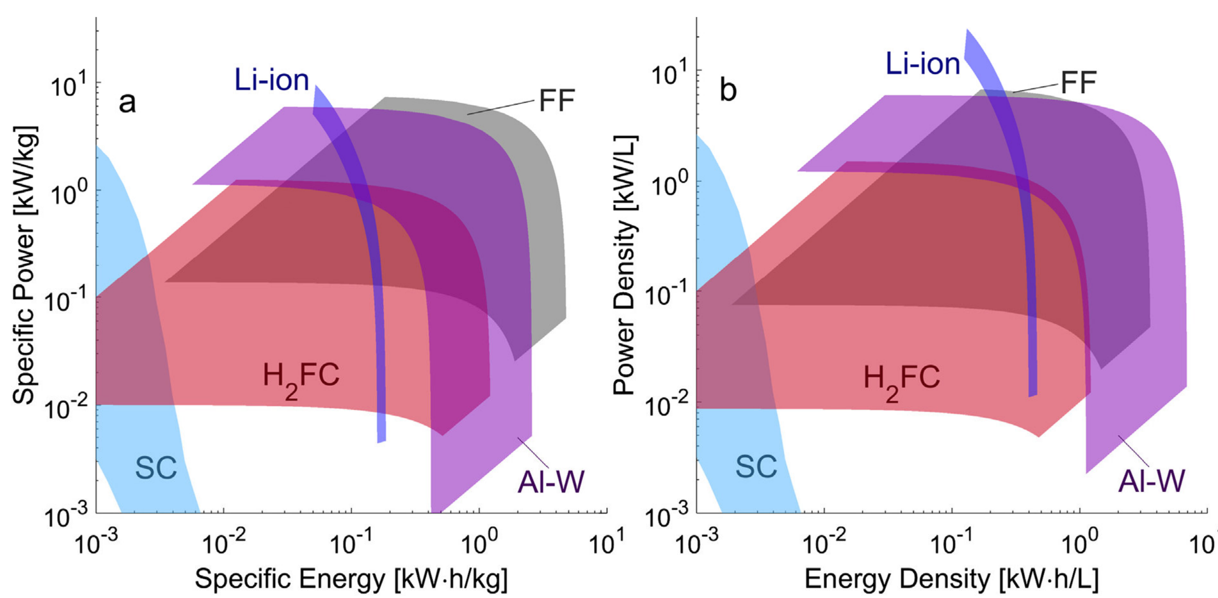

Fig. 8. Gravimetric (a) and volumetric (b) Ragone plots of various power sources: fossil-fueled internal-combustion (gasoline and diesel) engine (FF), aluminum-water for high- and low-temperature modes (Al-W), hydrogen fuel cells (H_2FC), Li-ion batteries (Li-ion), super-capacitors (SC). For clarity, different time bounds, corresponding to the maximum and minimum range, have been chosen for each application.