

## Aluminum-Rich Bulk Alloys: an Energy Storage Material for Splitting Water to Make Hydrogen Gas on Demand

The two major barriers to realizing a viable large-scale hydrogen economy are hydrogen storage and economically viable “green” hydrogen production. The current two preferred methods of hydrogen generation are water electrolysis and the decomposition of natural gas (methane). Even though both methods are approaching economic viability neither of them are “green.” Electrolysis to make hydrogen, although green in itself, uses grid electricity which is produced by burning coal; hence, electrolytically produced hydrogen gas is not green. Methane, CH<sub>4</sub>, when oxidized to produce hydrogen gas, also produces carbon dioxide, and water; hence, it is also not green.

### Online Resources

nanoHUB	Online presentation <a href="#">Aluminum: a safe, economical, high energy density material for energy storage, transport and splitting water to make hydrogen on demand</a>
YouTube	YouTube <a href="http://www.youtube.com/watch?v=dhroR7oELwA">http://www.youtube.com/watch?v=dhroR7oELwA</a>
YouTube	YouTube: Hydrogen powered engine demonstration
YouTube	YouTube: Aluminum-water reaction generating hydrogen demonstration
NPR	NPR: Talk of the Nation <a href="#">Scientists Seek New Ways to Generate Hydrogen</a>

### Energy Density

Hydrogen is stored mainly in very high-pressure tanks, liquid hydrogen, metal hydrides, etc. All, methods to date suffer from low energy density, either as low mass density or low volume density. And most methods suffer issues of reversible hydrogen liberation and regeneration.

### Energy Density: Al–H<sub>2</sub>+heat, diesel, liq. H<sub>2</sub>

- As **hydrogen** from splitting water:
  - 1 Kg H<sub>2</sub>: 142 MJ = 39.4 kWh combustible energy
  - 1 Kg Al makes 111 g of H<sub>2</sub> from 2 Kg of H<sub>2</sub>O = **4.4 kWh**
  - 1 gal (10 Kg) Al makes 44 kWh as hydrogen
  - 1 gal. diesel: 37 kWh
  - 1 gal. liquid hydrogen: 10 kWh
- As **heat** from splitting water:
  - 1 Kg Al: **4.4 kWh**
  - **Total energy, 1 Kg Al: 8.8 kWh (1Kg coal: 6.7 kWh!)**
  - Energy to electrolyze alumina to 1 Kg of Al: **12.9 kWh**
  - Total energy efficiency:  $(8.8/12.9) \times 100 = 68\%$
  - H<sub>2</sub> energy efficiency:  $(4.4/12.9) \times 100 = 34\%$

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On the other hand Al metal is a safe, abundant, renewable, high energy density (*see above*) material that when formed into an Al-rich alloy with only a 5 wt% mixture of gallium (Ga), indium (In), and tin (Sn), will efficiently and rapidly split water to make hydrogen on demand, (*see images 1 and 2*). Since the small Ga and In components are expensive but inert (*see image 3*), they can economically be recovered by mechanical separation, e.g. using a centrifuge.

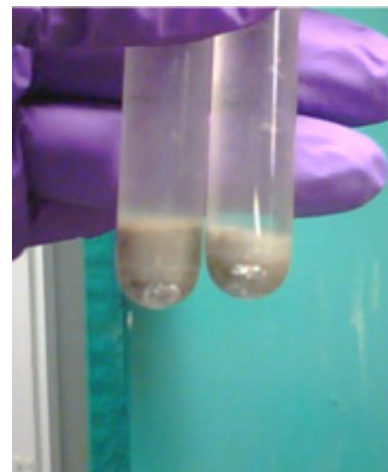


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95 wt.% Al – 5 wt.% GaInSn A sample of “50-50” Al-  
(vendor alloy)GaInSn splitting water



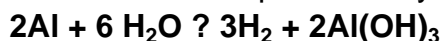
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Complete centrifuge recovery  
of GaInSn alloy

The reaction that produces hydrogen by splitting water with the Al alloy is:



**Technology sustainability and large scale use**

The total energy produce per kg of Al is 8.8 kWh; half as heat and half as the energy of combustion of hydrogen. The spent Al(OH)<sub>3</sub> is easily rejuvenated back to metallic Al using the well-established commercial Hall-Heroult electrolysis. Currently carbon electrodes are used, thus generating some carbon dioxide, but a commercial TiB<sub>2</sub> electrode technology for Al smelting has been developed by the De Nora Company to displace carbon electrodes. Since most smelting operations are done with hydroelectric power, i.e. not using fossil fuels, Al smelting could become totally green.

Before we need to worry about smelting aluminum hydroxide to recover Al, however, we can use the 400 billion kg of scrap metal on the planet that has already had its carbon footprint amortized. Therefore, this Al is green and can produce 44.4 billion kg of hydrogen or nearly 195 trillion Wh of hydrogen energy (*see below*).

**Technology sustainability & large scale use**

**World supply:**

- Al "reserve" in the planet's crust: about  $10^{13}$  Kg (as Al);  $1.2 \times 10^{12}$  Kg of H<sub>2</sub> made by splitting water =  $5 \times 10^{13}$  kWhrs of H<sub>2</sub> energy
- Current worldwide annual Al production: 32 billion Kg from bauxite;
- **400 billion Kg of scrap *impure* elemental Al available for recycling!** amount needed to supply 12% US annual energy consumption of about 100 quad BTU

**Large demand example fuel cell cars**

- If this 400 billion Kg of scrap Al were dedicated to splitting water, 44.4 billion Kg (195 trillion Wh) of H<sub>2</sub> could be made by splitting water
- At a 100 km/kg of H<sub>2</sub> efficiency,  $4.44 \times 10^{10}$  Kg of H<sub>2</sub> could power 100 million GM fuel cell cars 44,400 km before the Al reaction product would need to be converted back to Al metal

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### Scale of possible applications/markets

Finally, there are many applications for which this technology could be used:

- **Small:** 1-100 mW and 10 W-hrs, e.g. PDAs, laptops, i-pods, etc.
- **Medium:** 1-200 kW and 10-10000 kW-hrs, e.g. auxiliary power, cars, boats, fuel enrichment, etc.
- **Large:** > 5000kW and > million kW-hrs, e.g. trains, ships, subs, off-grid community power, base load peak power demand, storage for wind and solar power.