The Overall Energy Balance of the Hydrogen Bus in Berkeley, CA


Abstract

Hydrogen fuel cell buses are being tested in several cities in California as a clean, environmentally-friendly alternative to diesel buses. In Berkeley, a hydrogen bus system consists of grid electricity, electrolyzer, hydrogen compressor, hydrogen tanks, and a bus propelled by electrical motors driven by a 60 kW hydrogen fuel cell stack and a 600V auxiliary battery. We show that the overall energy efficiency of this system is 2-3 times lower than that of a diesel bus. The prototype hydrogen bus generates elsewhere 2-3 times the CO₂ emissions, and several times the NOₓ and SO₂ emissions of the clean diesel bus equipped with a catalyzed soot filter, and it costs 18 times more.

Introduction

Recently the automotive aspects of a “hydrogen economy” have received much government attention. A good example is the 178-page DOE report, Basic Research Needs for the Hydrogen Economy (13), which provides a thorough analysis of the various technologies required to produce the hydrogen-burning “Freedom CAR.”

A related DOE report, National Hydrogen Energy Roadmap (8), tabulates the planned hydrogen production capacity in the U.S., shown here as Table 1 with an extra column to specify the main energy/hydrogen sources for a hydrogen economy. As one can see, almost 90% of the future U.S. hydrogen will be produced from fossil fuels, petroleum hydrocarbons and coal. The hydrogen economy will not come cheaply. Between 2002 and 2004, the U.S. DOE alone will spend $337 million on research on the hydrogen infrastructure and fuel cell technology (12). The entire “Freedom CAR” initiative will cost $1.5 billion over 5 years (11).

¹To whom correspondence should be addressed, patzek@patzek.berkeley.edu. Spring
Table 1: Primary Energy/Hydrogen Sources for a Hydrogen Economy (8).

<table>
<thead>
<tr>
<th>Facility</th>
<th>Capacity tons/yr</th>
<th>( \text{H}_2 ) Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,000 neighborhood electrolyzers</td>
<td>4 millions</td>
<td>Coal</td>
</tr>
<tr>
<td>15,000 small reformers in refueling stations</td>
<td>8 millions</td>
<td>Methane</td>
</tr>
<tr>
<td>30 coal/biomass gasification plants</td>
<td>8 millions</td>
<td>Coal/sludge</td>
</tr>
<tr>
<td>10 nuclear water splitting plants</td>
<td>4 millions</td>
<td>Uranium</td>
</tr>
<tr>
<td>7 large oil&amp;gas SMR/gasification refineries</td>
<td>16 millions</td>
<td>Oil/Methane</td>
</tr>
</tbody>
</table>

Direct conversion of fossil fuels to hydrogen causes more \( \text{CO}_2 \) and other GHG gas emissions than burning of the same fuels. For example, burning coal, \( \text{C}+\text{O}_2 \rightarrow \text{CO}_2 \) produces 35 kJ/kgC of heat. Coal gasification, \( \text{C}+\text{H}_2\text{O} \rightarrow \text{CO}+\text{H}_2 \), consumes 10 kJ/kgC. This heat input is equivalent to burning 348 grams of extra coal per kilogram of gasified coal (5).

The goal of this paper is to illustrate the limitations of indirect hydrogen production from the most abundant fossil fuel in the U.S. – coal. In 2002, some 900 million metric tonnes of coal were burned in the U.S. to generate electricity (2). In 2001, 51 percent of electricity generated in the U.S. came from coal, with nuclear power being a distant second at 20.2 percent, and natural gas third at 16.9 percent (1). Per unit energy, natural gas was almost 4 times more expensive than coal (1) in 2001.

We set out to analyze an off-the-shelf technical solution that involves grid electricity, a 24 kg \( \text{H}_2 \)/day electrolyzer by Stuart Energy, Ontario, Canada, with multistage hydrogen compression to 250 bars, and a bus propelled by electrical motors driven by a 60 kW hydrogen fuel cell stack and a 600V auxiliary battery. This bus is a prototype, and three more buses are being built by a consortium of United Technologies of Connecticut (UTC Fuel Cells), ISE Research of San Diego, and Van Hool Bus Company of Belgium at a cost of $15 million (20) to the public. In comparison, a “clean” diesel bus (with a catalyzed soot filter) costs $275,000 (23), so the hydrogen bus is 18 times more expensive.

As an energy carrier that powers fuel-cells in a “clean” bus, hydrogen competes directly with gasoline or diesel fuel, and internal combustion engine. Therefore, it is fair to ask what is the overall energy efficiency of a particular process that evolves hydrogen used in a fuel-cell bus relative to that of an ordinary diesel bus? Thus, in this paper we evaluate the overall efficiency of the coal→electricity→compressed hydrogen→hydrogen bus process, and compare it with the efficiency of a crude oil→refinery→diesel fuel→diesel bus process. We recognize up front that the economics of hydrogen production from water electrolysis

---

2004 CE24 Class, Department of Civil and Environmental Engineering, University of California, Berkeley.
using grid electricity cannot be as good as that of steam-reforming of methane.

In the two irreversible and clearly unsustainable processes considered here, the primary sources of energy are fossil fuels, so the less efficient process will cause more air-polluting emissions, be more expensive, and deplete the overall stock of fossil fuels faster. Which one is it?

Conversion of Coal to Electricity and Hydrogen

We start the overall energy balance with 1 metric tonne (t) of coal. We assume the coal heating value (the energy released upon burning) to be 8,000 kWh/t (12,500 Btu/lb), (14). Mining and crushing of our coal requires 18 kWh/t (55,400 Btu/ton) (16), Chapter 2, Coal. Alternatively, if we used a hypothetical Eastern U.S. underground coal mine, the energy cost of mining and coal beneficiation, would be 135 kWh/t (420,000 Btu/ton) (16).

The indirect conversion of coal to hydrogen via water electrolysis requires several steps:

1. The crushed coal (< 8 cm) is brought to a coal-fired power station by rail. Let’s assume that the average distance is 500 miles. The energy cost of rail transport is 0.12 kWh/t-mile (9), or 60 kWh/t.

2. The coal chunks are pulverized by roller mills powered by electrical motors to a 70 percent, #200 sieve minus powder, and this powder is moved by hot air to the boiler furnaces (18). The pulverization cost is 35-73 kWh/t, and we pick 50 kWh/t.

Notice that all the steps prior to burning the coal powder used up only 128 kWh/t or 1.6% of the coal heating value. If we used an Eastern U.S. coal mine, this cost would be 245 kWh/t, or 3%.

3. The pulverized coal is burned to generate electricity. The overall efficiency of an advanced pulverized-coal power plant may be as high as 45% (15). This efficiency corresponds to the Rankine cycle efficiency of 58%, steam turbine efficiency of 92%, generator efficiency of 98.7%, boiler efficiency of 92%, and auxiliary efficiency of 93%, (19), page 20. At this plant efficiency, the steam turbines operate at 300 bars and 600°C. Existing power plants have overall efficiencies in the range of 30-40%. We assume that the overall efficiency of an excellent existing power plant is 40%. In view of the age and technical conditions of many U.S. power plants, this may be an optimistic assumption.

4. The generated electricity is delivered to end-users through transmission wires. Energy losses in a large electrical system range from 5-8% (10). We pick 7% in transmission energy losses.

5. Grid AC electricity must be rectified. We assume the rectifier efficiency to be 97%.
At this stage we have available to us

\[(8,000 - 128) \times 0.40 \times (1 - 0.07) \times 0.97 = 2,840 \text{ kWh/t} \quad (1)\]

or 35.5% of the coal heating value. This *useful* energy will now be applied to evolve hydrogen from water and compress it to the desired pressure.

The hydrogen plant idles for a good part of the day at an assumed cost of only 10% of the input electricity to keep the electrolyzers warm, continuously release hydrogen into the atmosphere, cf. (22), etc... This leaves us with 2,556 kWh/t as rectified grid electricity to electrolyze the hydrogen and compress it in the last three steps of the process:

6. In theory, water is split into \( \text{H}_2 \) and \( \text{O}_2 \) in reactions that can be driven by a potential difference of 1.23V, corresponding to the free energy input of 237 MJ/kmole of \( \text{H}_2 \), e.g., (13). In practice, extra voltage is needed to also evolve oxygen in a multi-step process that involves 4 electrons and intermediates. The cell efficiency is calculated as the theoretical voltage divided by the applied one. For 1.6V, this efficiency is \( 1.23/1.6 \times 100 = 77\% \), corresponding to the energy input of \( 237/0.77 = 308 \) MJ/kmol=42.8 kWh/kg \( \text{H}_2 \). Often, electrolysis is helped by heating the cells, with an additional expenditure of energy.

7. The hydrogen is compressed from the atmospheric pressure to 250 bars. Compression is energy intensive. To compress 1 kg of \( \text{H}_2 \) to 250 bars adiabatically requires (6) 4.22 kWh, and isothermally 1.70 kWh. Energy efficiency of multistage compression with interstage cooling is between adiabatic and isothermal compression. Since problems with heat transfer from the low-heat-conductivity composite hydrogen tanks are serious, the overall efficiency of a multistage compressor discharging into an insulated tank will be closer to adiabatic, rather than isothermal efficiency. Optimistically, we assume a midpoint value of 3 kWh/kg \( \text{H}_2 \).

8. Finally, from 1 metric tonne of coal we obtain

\[
2,556 \text{ kWh/t coal} / (42.8 \text{ kWh/kg} \text{ H}_2 + 3 \text{ kWh/kg} \text{ H}_2 ) = 56 \text{ kg of H}_2 \quad (2)
\]

The high heating value of hydrogen is (6) 142 MJ/kg or 39 kWh/kg. Therefore, by burning 1 metric tonne of coal with the *in situ* heating value of 8,000 kWh, we get 2,200 kWh as the high heating value of hydrogen compressed to 250 bars, or 27.5% of the original coal heating value.

**Hydrogen vs. Diesel Bus**

AC Transit measured (21) the average fuel efficiency of 4.25 km/l (10 miles/gallon) diesel equivalent for the hydrogen bus. It also measured the average fuel efficiency of an ordinary bus as 2.55 km/l (6 miles/gallon) of diesel fuel. With the diesel fuel density of 0.84 kg/l,
the hydrogen bus drives 5 km by burning 1 kg of diesel equivalent, and the ordinary bus drives 3 km per kg of diesel fuel.

The low heating value of diesel fuel is \(3\) 11.86 kWh/kg. The same high heating value is contained in \(12/39 = 0.3\) kg of \(H_2\). Therefore, our hydrogen bus will drive \(5 \times 56/0.3 = 933\) km by effectively burning 1 metric tonne of coal, and its specific primary energy use is 8.6 kWh/km.

To drive the same distance, the ordinary diesel bus will use 307 kg of diesel fuel, equivalent to 3,640 kWh. The energy losses in a modern refinery are of the order 2-3\% of the heating value of crude oil \(25\). If we add another 2\% penalty for the recovery and transportation of crude oil to the refinery, the primary source energy used by the diesel bus is \(3640/0.95 = 3800\) kWh, and its specific primary energy use is 4 kWh/km.

Therefore, the diesel bus is \(8,000/3,800 = 2\) times more efficient than the hydrogen bus. If the overall efficiency of the power plant is 30\%, this ratio increases to almost 3. In plain English, given the same amount of primary fossil energy the diesel bus will drive 2-3 times as far as the hydrogen bus. Conversely, for the same number of miles driven, the hydrogen bus will cause 2-3 times more CO\(_2\) emissions elsewhere, and many times more SO\(_2\) and NO\(_x\) emissions from the power plant \(24\). A good diesel bus realistically emits about 2 kilograms of GHG per kilometer \(7\). It should be stated, however, that in California alone the diesel engines emit about 30,000 tons per year of highly cancerogenic sub-micron soot \(4\). These latter emissions can be reduced by 80-90\% with the catalyzed soot filters \(17\) at an extra cost.

Conclusions

The overall energy efficiency of the diesel bus is at least two times higher than that of the hydrogen bus, when the hydrogen is generated from grid electricity as in the Richmond, CA, pilot project.

The overall CO\(_2\) emissions are therefore more than twice as high for the hydrogen bus as for the diesel bus. In addition, the SO\(_2\) and NO\(_x\) emissions from a coal-fired power plant are significantly higher than those from a diesel bus.

On the other hand, the soot emissions from the dirty U.S. diesel engines are high and may be unacceptable in the cities. In some circumstances, it may be required that the GHG emissions occur elsewhere and from point-sources, especially if these gases can be sequestered, but this is yet another story….

References and Notes


