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

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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 CO_2 emissions, and several times the NO_x and SO_2 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*).

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Table 1: Primary Energy/Hydrogen Sources for a Hydrogen Economy (*8*).

Facility	Capacity tons/yr	H_2 Source
100,000 neighborhood electrolyzers	4 millions	Coal
15,000 small reformers in refueling stations	8 millions	Methane
30 coal/biomass gasification plants	8 millions	Coal/sludge
10 nuclear water splitting plants	4 millions	Uranium
7 large oil&gas SMR/gasification refineries	16 millions	Oil/Methane

Direct conversion of fossil fuels to hydrogen causes more CO_2 and other GHG gas emissions than burning of the same fuels. For example, burning coal, $C+O_2 \rightarrow CO_2$ *produces* 35 kJ/kgC of heat. Coal gasification, $C+H_2O \rightarrow CO+H_2$, *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 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), I*SE 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

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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 600^0C. 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

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

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 H_2 and 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 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 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 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 H_2.

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

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

   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

1. U.S. Energy Information Agency. Electricity Info Card 2001. WWW, 2003. http://-www.eia.doe.gov/neic/brochure/elecinfocard.html.

2. U.S. Energy Information Agency. U.S. coal consumption by end-use sector 1997-2003. WWW, 2003. http://www.eia.doe.gov/cneaf/coal/quarterly/html/t29p01p1.html.

3. API. Alcohols: A technical assessment of their application as motor fuels. API Publication No. 4261, Washington, D.C., July 1976.

4. California Air Resources Board. Emission inventory 1995. WWW, 1997. Technical Support Division, October 1997: http://www.nrdc.org/air/transportation/ebd/-chap1.asp.

5. W. Bobrownicki, A. Justat, and S. Pawlikowski. *Inorganic Chemical Technology.* Wydawnictwa Naukowo-Techniczne, Warsaw, 1965.

6. U. Bossel, Eliasson B., and G. Taylor. The future of the hydrogen economy: Bright or bleak – Final Report, april 15. Technical report, 2003. http://www.efcf.com/-reports/hydrogen_economy.pdf.

7. P. Coroller and G. Plassat. Comparative study on exhaust emissions from diesel- and CNG-powered urban buses. WWW, 2003. http://www.orau.gov/deer/presentations/-session5/7. Ademe - Bus CNG.Diesel.pdf.

8. M Davis, F. Balog, G. Nemanich, A. Katsaros, Ogden J., and A. Niedzwiecki. National hydrogen energy roadmap – Toward a more secure and cleaner energy future for America - production – delivery – storage – conversion – applications – public education and outreach. Technical report, Based on the results of the National Hydrogen Energy Roadmap Workshop Washington, DC, April 2-3, 2002, U.S. DOE, 2002. http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf.

9. S. C. Davis and D. N. McFarlin. Transporation energy data book: Edition 17. Report, Oak Ridge National Laboratory, Center for Transportation Analysis, 1997.

10. Energy dictionary. WWW, 2003. http://www.energyvortex.com/energydictionary/-energy_loss__transmission_loss.html.

11. DOE. Freedom CAR (Cooperative Automotive Research Initiative. WWW, 2003. http://www.eere.energy.gov/vehiclesandfuels/.

12. DOE. Hydrogen Fuel Cells & Infractructure Technologies Program. WWW, 2003. http://www.eere.energy.gov/hydrogenandfuelcells/mypp/ - Appendices.

13. M. Dresselhaus and *et al.*. Basic research needs for the hydrogen economy. Technical report, Argonne National Laboratory, Basic Energy Sciences, U.S. DOE, 2003. http://www.sc.doe.gov/bes/hydrogen.pdf.

14. American Coal Foundation. Types of coal. WWW, 2003. http://www.ket.org/Trips/-Coal/AGSMM/agsmmtypes.html.

15. A. B. Gill. *Power plant performance*. Butterworths, London, 1984.

16. BCS Inc. Energy and environmental profile of the U.S. mining industry. Report, U.S. DOE, Office of Energy Efficiency and Renewable Energy, 2002.

17. R. M. Kakwani, K. Voss, J. Patchett, and K. Grimston. Combined catalyzed soot filter and SCR catalyst system for diesel engine emission reduction. 6th Diesel Engine Emissions Reduction (DEER) Workshop, August 20-24, San Diego, CA, 2000. http://www.osti.gov/fcvt/deer2000/kakwanpa.pdf.

18. D. F. Pflughoeft-Hassett, E. A. Sondreal, E. N. Steadman, K. E. Eylands, and B. A. Docter. Production of coal combustion by-products: Processes, volumes, and variability. Technical report, Energy and Environmental Research Center, University of North Dakota, 2000. http://www.ott.wrcc.osmre.gov/library/proceed/ccb2000/-session1.pdf.

19. H. Termuehlen and W. Emsperger. *Clean and Efficient Coal-fired Power Plants - Development toward advanced technologies*. ASME Press, New York, 2003.

20. AC Transit. The hydrogen age comes to Richmond, California and the San Francisco Bay Area, 2002. http://www.actransit.org/pdf/fuelcell_hydrogenrelease.pdf.

21. AC Transit. AC Transit demonstrates 30' hydrogen fuel cell hybrid-electric transit bus, 2003. http://www.actransit.org/onthehorizon/fuelcell.wu.

22. T. K. Tromp, R.-L. Shia, M. Allen, J. M. Eiler, and Y. L. Yung. Potential environmental impact of a hydrogen economy on the stratosphere. *Science*, 300:1740–1742, 2003.

23. Green Diesel Technology Vehicles. WWW, 2003. http://www.greendiesel-technology.com/news48.html.

24. Keith D. W. and A. Farrell. Rethinking hydrogen cars. *Science*, 301:315–316, 2003.

25. Worrell, E. Personal communication, 2003. Estimated from the information by refining companies.