To: science_letters@aaas.org
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Subject: ~10x error in energy-hydrogen conversion
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Eiler *et al.* state (*1*) that replacing 1 TW of fossil-fuel energy flow requires 1.06 GT/y of hydrogen (H_2), yielding a "discrepancy whose source is unclear to us." An elementary calculation (*2, 3*) shows the actual hydrogen equivalent is an order of magnitude smaller. Their error has three layers.

First, substituting for 1 TW of fossil-fuel energy flow requires 0.263 GT/y of H_2, not 1.06 GT/y, based on energy content alone (*2*). Second, that's not the right comparison. Because a good H_2 fuel cell can use H_2 ~2-3x as efficiently as a good car engine uses gasoline (*3*), and H_2 enjoys a similar efficiency advantage in delivering heat and power to buildings, ~2-3x less H_2 than fossil fuel would be needed to do the same tasks. Thus to replace the functions provided by 1 TW of fossil fuel energy would take roughly 0.08 to 0.12 GT/y of H_2, ~8-12x less than Eiler *et al.* stated.

Eiler *et al.*'s first (4x) error appears to have come from uncritically adopting a confusing Department of Energy footnote (*4*) that they then incorrectly applied. The footnote described not (as they supposed) how much fossil fuel a given amount of H_2 can replace, but rather how much fossil fuel must be burned in a classical steam power plant to make enough electricity to produce a given amount of H_2 by electrolysis. A nominal 33%-efficient thermal power plant and 75%-efficient electrolyzer (neglecting distribution losses) requires four units of fossil fuel to produce one unit of H_2—so much, hence so costly, that almost no H_2 is produced that way.

Eiler *et al.* had previously (*5*) overstated leakage from a large-scale H_2 energy system by about two orders of magnitude. When three letters noted this and other serious errors (*6–8*), they redefined their claimed leakage source as boiloff from liquid-H_2-fueled cars (*9*). In fact, liquid-H_2 fuel is uneconomic, unnecessary, and unlikely for cars, but even if it were used, its minor boiloff wouldn't be vented (*10*). In both cases, the authors' citations systematically contradicted their thesis. Their new ~10x overstatement of H_2 requirements casts further doubt on their grasp of the subject.

Their logic is equally dubious. Their initial claim that 10–20% H_2 leakage "should be expected" (*5*) was called "grossly overstated" by the Assistant Secretary of Energy (*11*). In response, they first misstated (*1*) that they'd said only "leakage of up to 10% to 20% should be considered," then cited in rebuttal two correct but irrelevant facts about the same DOE workshop report they'd previously misinterpreted (*4*): first, it says "Leakage rates much greater than 1% are likely if no action is taken to engineer systems in advance to minimize hydrogen leakage," and second, the report "does not discuss the possibility that...leakage rates could be less than 1%." (Of course: that wasn't the workshop's purpose.) The DOE report, they concluded, must therefore be considered "consistent with" their original claim of 10–20% leakage. Such creative inference from what their source *doesn't* say can "prove" any claim from any citation, but it's not even good rhetoric, let alone good science.

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1. J.M. Eiler, T.K. Tromp, R.-L. Shia, M. Allen, Y.L. Yung, *Science* **302**, 1332 (2003).

2. 1 W or 1 J/s of energy flow throughout 1 year (8,766 h x 3,600 s/h or ~π x 10^7 s/y) is an annual energy flow of 31.56 MJ. Since the Lower Heating Value of H_2 is 120 MJ/kg, equivalent energy would be contained in 31.56/120 = 0.263 kg of H_2, or 4.03 times less than the claimed 1.06 kg.

3. A.B. Lovins, "Twenty Hydrogen Myths" (Rocky Mountain Institute, Snowmass, CO, 2003) (available at www.rmi.org/images/other/E-20HydrogenMyths.pdf). DOE states the factor is 2.5: D. Garman, "Freedom car: 'free ride' or fuel economy savior? An e-EFFICIENCY NEWS Point-Counterpoint," Alliance to Save Energy newsletter, 21 May 2003, available at www.ase.org/e-FFICIENCY/archives/2003_05.htm. (Burning H_2 in an internal-combustion engine reduces its efficiency advantage over hydrocarbons to ~1.3–1.5 but compromises its economic case.) In stationary applications, onsite H_2 cogeneration or trigeneration typically offers at least twice the efficiency of a central fossil-fueled power station plus an onsite combustion heater.

4. "Basic Research Needs for the Hydrogen Economy," Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use (Office of Science, U.S. Department of Energy, Washington, DC, 2003) (available at www.sc.doe.gov/bes/hydrogen.pdf), at p. 9, n. 1, which reads in full: "In terms of energy use, 1 gigawatt (GW) of power — the output of most light-water nuclear reactors — corresponds to approximately 1.06 million tons/year (Mtons) of hydrogen. One terawatt-year (TW-yr) of energy is equivalent to 1.06 gigatons (Gtons) of hydrogen. The 3.3 TW use of fossil fuels in 2000 would thus correspond to approximately 3.5 Gtons of hydrogen." Both Eiler *et al.* and the DOE workshop report adopted this erroneous conversion factor, apparently without checking its derivation, but DOE is now aware of the error and is currently preparing to publish a correction (D. Garman, personal communication, 30 December 2003).

5. T.K. Tromp, R.-L. Shia, M. Allen, J.M. Eiler, & Y.L. Yung, *Science* **300**, 1740 (2003).

6. A.B. Lovins, *Science*, **302**, 226 (2003).

7. D.M. Kammen & T.E. Lipman, *Science*, **302**, 226 (2003).

8. P.E. Lehman, *Science*, **302**, 227 (2003).

9. J.M. Eiler, T.K. Tromp, R.-L. Shia, M. Allen, Y.L. Yung, *Science* **302**, 228 (2003).

10. A.B. Lovins, "Rebuttal to Tromp *et al.*'s Response," available at www.sciencemag.org/cgi/eletters/302/5643/226b?ck=nck, with full text at www.rmi.org/images/other/E03-08_SciRebuttalTromp.pdf.

11. D. Garman, *Science*, **302**, 1331 (2003).