LETTERS

Letters to the Editor

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Assessing the Future Hydrogen Economy

T. K. TROMP *ET AL.*'S REPORT "POTENTIAL environmental impact of a hydrogen economy on the stratosphere" (13 June, p. 1740) is a welcome addition to the analysis of potential future energy scenarios. However, several key assumptions made in the study represent unlikely extreme cases that are not well connected to current or likely future levels of hydrogen usage or system leakage. As a result, the baseline "scenario" presented in the paper is not a useful starting point for discussion and analysis.

There are three primary assumptions in the study that, in our view, should be considered more carefully. First, the assumed hydrogen leakage rates of 10 to 20% are based on early analysis of early-generation, small-scale hydrogen delivery systems and are not consistent with other studies, including those cited by the authors, that have measured and projected rates of less than 1 to 2% (and up to 10% only in extreme cases) (*1*). Thus, based on the hydrogen leakage rate estimates available, and a detailed analysis by one of our colleagues of overall hydrogen leakage from key sources including pipelines, storage systems, compressors, pumps, and vehicles, we believe that leakage rates of 1 to 2% are most likely for mature hydrogen delivery and end-use systems, with the lower-end estimates corresponding to gaseous hydrogen delivery systems, and the higher end to liquid hydrogen delivery (*2*). This difference alone results in Tromp *et al.* beginning their model with roughly a factor of 10 overestimate in hydrogen leakage to the atmosphere.

Second, the study assumes that hydrogen fuel cells will completely supplant "all current technologies based on oil or gasoline combustion" (p. 1740). If fuel cells were to ever fully supplant fossil fuels, it would certainly not take place for many decades. Penetration levels for hydrogen of 30% into oil and gasoline markets over the next half century would constitute a major success. Taken together, these two extreme high-end assumptions result in a 30-fold exaggeration in modeled hydrogen emissions. A scenario with these assumptions replaced by more realistic ones would result in H_2 release rates that would have far smaller or negligible impacts on the stratospheric concentration of water vapor.

Third, the timing of the hydrogen economy envisioned by the authors is dubious. As they note, if the hydrogen economy were to reach the scale they envision by 2050, when the ozone hole is (we hope, based on current trends) largely repaired, the H_2 release would have little or no atmospheric impact, even based on their own assumptions. In fact, most assessments of the likely timing of future large-scale use of hydrogen see 2020 as a time when it is only beginning to increase significantly. Thus, by the time significant amounts of hydrogen are added to the atmosphere, because of the potential for soil uptake of anthropogenic hydrogen emissions and new control technologies, the levels of CFCs in the atmosphere should be low enough to prevent a significant climate impact due to any impacts on stratospheric moistening and cooling of hydrogen emissions.

We do not agree with some of the statements made by Tromp *et al.* that portray their rather extreme case as if it were middle ground—to wit, the phrase "[m]ore or less dramatic scenarios are equally imaginable." In fact, a more extreme high-emissions case is hardly imaginable, even with relatively conventional hydrogen storage and dispensing technologies. When the prospects for future hydrogen storage systems based on metal hydrides, chemical hydrides, and carbon nanotubes are considered (which could result in further dramatic reductions in hydrogen emissions/losses), it is likely that the leakage rates will be decreased still further. In fact, our estimates indicate that a hydrogen economy would result in an overall increase in stratospheric OH^-, not the decrease of the Tromp *et al.* assessment.

> **"[S]everal key assumptions made in the [Tromp *et al.*] study represent unlikely extreme cases that are not well connected to current or likely future levels of hydrogen usage or system leakage."**
>
> —*KAMMEN & LIPMAN*

DANIEL M. KAMMEN AND TIMOTHY E. LIPMAN
Center for Interdisciplinary Distributed Energy Research (CIDER), Goldman School of Public Policy, Energy and Resources Group, University of California, Berkeley, Berkeley, CA 94270–3050, USA.

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2. M. A. Delucchi, *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Vehicles, and Modes, Electricity Use, Heating and Cooking Fuels, and Materials* (UCD-ITS-RR-03-04, Institute of Transportation Studies–Davis, University of California, Davis, 2003).

PRIOR TECHNOLOGY ASSESSMENT IS VITAL for precautionary environmental protection, but T. K. Tromp *et al.*'s attempt ("Potential environmental impact of a hydrogen economy on the stratosphere," Reports, 13 June, p. 1740) inadvertently misleads by assuming that a large-scale hydrogen energy system will leak ~10 to 20% of its throughput. That is 1 to 2 orders of magnitude too high. If Tromp *et al.* were right, then of the total anthropogenic H_2 emissions they cite (15 ± 10 Tg/year), all previously believed to come from incomplete combustion and methane emissions of fossil fuels and biomass, 5 to 10 Tg/year would instead be due to leaks from today's ~50 Tg/year global production of industrial H_2. No such source term has been observed.

H_2 losses, say Tromp *et al.*, "are reasonably projected to be on the order of 10% [(*1*)]. Losses during current commercial transport of H_2 are substantially greater than this [(*2*)], suggesting to us that a range of 10 to 20% should be expected." But their citations don't support this view.

Their first citation (*1*) doesn't "reasonably project" potential 10% H_2 losses, but mentions that figure only as a crude worst-case example and says 2 to 3% "seems… more realistic," even assuming liquid (L) H_2 system losses of ~1 to 10% and an entirely LH_2-fueled global aircraft fleet of "cryoplanes." Moreover, its senior author, Zittel, confirms (*3*) that this 2 to 3% was meant not as an actual emission estimate, but only as the hypothetical leakage rate that would cause a global H_2 system to emit about as much H_2 as today's energy system. The actual H_2 leakage his paper states (*1*), for Germany, is only ~0.1%, compared with ~0.7% for Germany's natural-gas system: H_2's greater mobility is more than offset by the industry's avoidance of leak-prone threaded and compression fittings.

Tromp *et al.*'s second citation (*2*) gives no loss figures for "current commercial transport of H_2." It mentions only daily rates of boil-off—usually reused as fuel, not vented—from small, expensive truck and rail containers for LH_2. But LH_2 is so costly to produce and distribute (*4*) that it is only 10^{-3} of current H_2 production, mainly for space rockets, and is unlikely to compete in any significant future markets except cryoplanes, which should have low LH_2 losses.

For potential gaseous H_2 use, today's natural-gas losses represent a reasonable upper bound, because economy and safety would require even lower H_2 losses. Natural-gas system losses worldwide average ~1%, certainly <1.5% (*5–7*), but only ~0.1 to 0.5% for well run systems in industrial countries, where ~0.05% is expected in new distribution systems (*8*).

Tromp *et al.*'s main citation (*1*) notes that even if half of current world energy use were supplied by ~1.3 Pg/year of H_2 (*9*), a high loss rate of ~2 to 3% would release ~26 to 40 Tg of H_2 per year—comparable to today's ~11 to 57 (or, say Tromp *et al.*, 15 ± 10) Tg of H_2 per year releases from the fossil-fuel economy that such a H_2 economy could partly or wholly displace (*1*, *10*). But this comparison is conservative. Actual plausible H_2 releases would be 1 to 2 orders of magnitude lower than this; 1.3 Pg of H_2 per year could deliver about as much energy service as now, not half as much, due to H_2's doubled end-use efficiency (*11*), and renewable sources would displace H_2-releasing fossil-fuel systems and, if used directly, the H_2 carrier too.

Thus, a H_2 economy, rather than increasing anthropogenic H_2 emissions by ~4 to 8 times, as Tromp *et al.* fear, would probably reduce them by one or perhaps two orders of magnitude, to a level well below natural H_2 releases. Not only is it "likely that [H_2] emissions could be limited or even made negligible, although at some cost," as Tromp *et al.* agree, but this would merely reflect normal practice, at minor cost, in today's hydrogen and natural-gas industries.

AMORY B. LOVINS

Rocky Mountain Institute, 1739 Snowmass Creek Road, Snowmass, CO, 81654–9115, USA. E-mail: ablovins@rmi.org

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2. S. A. Sherif, N. Zeytinoglu, T. N. Veziroglu, *Intl. J. Hydrogen Energy* **22**, 683 (1997).
3. W. Zittel, personal communications. Even if LH_2 did become a major item of commerce, a Québec-Hamburg LH_2 marine transport system could readily have zero boil-off losses, as described by (*12*).
4. B. Eliasson, U. Bossel, in *Proceedings Fuel Cell World* (Morgenacherstrasse, Oberrohrdorf, Switzerland), pp. 367–382 (available at www.evworld.com/databases/storybuilder.cfm?storyid=471 and www.woodgas.com/hydrogen_economy.pdf).
5. M. Q. Wang, H.-S. Huang, *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas* (ANL/ESD-40, Argonne National Laboratory, Argonne, IL, 1999), p. 36 (available at www.transportation.anl.gov/pdfs/TA/13.pdf).
6. M. Q. Wang (*5*) (personal communication) kindly provided further Gas Research Institute/USEPA, USEIA, Canadian, General Motors, and International Energy Agency data indicating that "a [global natural-gas] leakage rate of 1% is reasonable. The highest rate could be 1.5%. The rate would definitely not go to the 5 to 10% range." For example, total natural-gas losses from a West Siberian field to German wholesalers, 6000 km away, were measured at ~1% in 1996–97 (*9*).
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9. Annex *"Full Background Report" to the GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—A European Study* (L-B-Systemtechnik GmbH, Ottobrunn, Germany), pp. 74–75 (available at www.lbst.de/gm-wtw).
10. Half of 2000 world primary consumption of 368 EJ/year, at H_2's higher heating value (142 MJ/kg). However, H_2's end-use efficiency, chiefly in fuel cells, can be about twice that of fossil fuels, so about the present total amount of energy service would be provided.
11. A. B. Lovins, *Twenty hydrogen myths* (Rocky Mountain Institute, Snowmass, CO, 12 July 2003) (available at www.rmi.org).
12. J. Gretz, B. Drolet, D. Kluyskens, F. Sandmann, O. Ullmann, *Int. J. Hydrogen Energy* **19**, 169 (1994).

IN THEIR RECENT REPORT "POTENTIAL environmental impact of a hydrogen economy on the stratosphere" (13 June, p. 1740), T. K. Tromp *et al.* examine the effect that emissions of hydrogen from the widespread use of fuel cell technology would have on the atmosphere. Using modeling, they report that increased molecular hydrogen concentration in the atmosphere would lead to stratospheric cooling and ozone depletion, among other effects.

Tromp *et al.* make assumptions regarding the magnitude of hydrogen emissions that would result from a complete switch to a hydrogen economy. They base their assumptions on previous work by Zittel and Altmann (*1*) and Sherif *et al.* (*2*). They claim from Zittel and Altmann that losses of hydrogen "have been reasonably projected to be on the order of 10%." Zittel and Altmann, however, give actual losses of gaseous hydrogen from an existing hydrogen pipeline grid in Germany to be 0.1% and losses from transporting liquid hydrogen to range from 1 to 10%. They give 2 to 3% as a "more realistic" estimate of losses for liquid hydrogen.

Citing Sherif, Tromp *et al.* estimate losses to be even higher, suggesting "that a range of 10 to 20% should be expected." Sherif *et al.* do say that "boil-off losses associated with the storage, transportation, and handling of liquid hydrogen can consume up to 40% of its available combustion energy." However, they later give boil-off rates for liquid hydrogen dewars that allow calculation of reasonably expected losses. For example, a tanker-truck-sized tank would lose about 0.4%/day, so for a 5-day delivery run, total losses would be only 2%. Losses from much larger storage tanks would be significantly less per day.

If Tromp *et al.* had assumed these smaller losses, their results would be far less striking. Further, the simple expedient of catalytically oxidizing the vented hydrogen would reduce the effect to an almost negligible level. Indeed, we should continue to be vigilant in determining the effect of technology change on the global environment, but it does not seem that hydrogen emissions will undermine the obvious benefits of a hydrogen economy.

PETER A. LEHMAN

Schatz Energy Research Center, Environmental Resources, Engineering Department, Humboldt State University, Arcata, CA 95521, USA. E-mail: pal1@humboldt.edu

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Response

THE LETTER WRITERS SUGGEST THAT emissions of H_2 associated with a hydrogen economy could not be as large as the upper end of the range we consider. We have two responses.

First, the Letter writers neglect technologies that are important parts of current plans for a hydrogen economy and that are prone to H_2 losses. For example, they do not mention or actively downplay liquid hydrogen as a medium for transportation or storage. In doing so, they disagree with the plans and investments of the Department of Energy (DOE) and automobile manufacturers and with other predictions regarding likely components of a hydrogen economy (*1–11*). At issue is the performance of consumer devices, most importantly, cars, whose capabilities depend on storing H_2 in a dense form. Vehicles with low-pressure tanks of hydrogen gas have negligible leaks but poor range; in contrast, those with liquid hydrogen tanks can have ranges similar to modern gasoline-burning cars (~400 km) but have significant boil-off losses (*3*, *7*, *8*). Sorbants are a third alternative but currently require large amounts of storage media and might not compete in cost and performance with the alternatives (*2*, *3*, *7*). The superior range of fuel cell cars with liquid hydrogen tanks suggests they could outcompete the alternatives on the open market, despite less effective fuel efficiency. A recent DOE statement of objectives (*1*) concludes: "Compressed and liquid hydrogen technologies represent the state-of-the-art for hydrogen storage systems. They will be instrumental in the near-term demonstration of hydrogen-powered vehicles and fueling stations."

> "[O]ur study is not an indictment of specific hydrogen technologies, but rather a warning of issues that should be recognized and avoided now so they need not be suffered through or mitigated in the future."
>
> —*TROMP* ET AL.

This DOE report sets the goal of developing, by 2005, H_2 storage systems small enough for passenger vehicles and capable of losing 0.1% of their stored hydrogen per hour. This broadly agrees with internal reports from automobile manufacturers that liquid hydrogen tanks of suitable size for personal automobiles lose 2 to 4% of their stored hydrogen per day and with independent summaries of the performance of such technologies (*6*, *7*, *11*, *12*). Assuming that drivers will fill up weekly and leave cars parked and partially filled most of the time, vehicles with such tanks could lose amounts of hydrogen within, or above, the range we discussed. Naturally, emissions from an entire system of hydrogen production, transport, and vehicle consumption would be at least this large. Thus, the upper end of our range of emission estimates should at least be considered.

More generally, it is important to realize that this is a debate about the performance of machines that do not exist. For this reason, our study is not an indictment of specific hydrogen technologies, but rather a warning of issues that should be recognized and avoided now so they need not be suffered through or mitigated in the future. We hope that the current methods of storing H_2 at high densities will improve or be replaced by better alternatives. Similarly, one can imagine ways of reclaiming or mitigating some gaseous H_2 emissions. The DOE statement cited above (*1*) sets goals of reducing hydrogen losses by factors of 10 to 20 relative to their 2005 benchmark within a decade. However, such progress will depend on factors in addition to environmental impact, fuel efficiency, and engineering achievements, e.g., cost, durability, performance, safety, and consumer preferences. Finally, whatever more or less leaky technologies might exist in the future, we must keep in mind that a fully developed hydrogen economy will involve annual production, transport, and consumption of amounts of H_2 several times greater than the total quantity in the atmosphere today. Given the magnitude of this undertaking, it would be foolish not to consider the consequences of accumulated accidental emissions, whatever their sources.

Second, we wish to reemphasize that current understanding of the budget of atmospheric H_2 is insufficient to accurately predict the relationship between emissions and steady-state concentrations, principally because the response of soil uptake to additional atmospheric loading is unknown. It is possible that lower emissions than we discuss could lead to higher steady-state concentrations than we modeled, or visa versa. Our understanding of this problem is analogous to the scientific grasp of the atmospheric CO_2 budget several decades ago: The identities of important sources and sinks were recognized, but there was no basis for confidently projecting concentration as a function of anthropogenic emissions (in fact, this remains difficult). In the face of this uncertainty, models describing the consequences of increased atmospheric loading are key to defining the level and nature of potential risk and to identifying the subjects that must be studied in more detail before producing accurate quantitative predictions.

Finally, we respond to two lesser points raised in these Letters: Lovins suggests that H_2 cannot leak from existing industrial systems of production and transport at significant rates because leaks from these systems do not appear in the published budgets. This is a misleading argument: The anthropogenic emissions appearing in recent atmospheric H_2 budgets (*13*, *14*) are calculated as a multiple of better-known CO emissions based on measured H_2/CO ratios in car exhaust and urban air. Emissions from production and transport of H_2 are not included or considered when estimating uncertainties in anthropogenic emissions. Current H_2 production and transport is simply a separate and additional anthropogenic source that lies hidden within the nearly factor of 2 uncertainties in global production from all sources. Kammen and Lipman argue that a hydrogen economy will not appear for 50 years. We neither support nor contest this prediction and, in any event, acknowledge that possibility and discuss its implications in our Report.

JOHN M. EILER, TRACEY K. TROMP, RUN-LIE SHIA, MARK ALLEN, Y. L. YUNG

Division of Geological and Planetary Sciences, California Institute of Technology, Mail Code: 100-23, Pasadena, CA 91125, USA.

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