

COMMENTARY

Reply to comment on “How Green is Blue Hydrogen?”

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Funding information

The Park Foundation; College of Agriculture and Life Sciences, Cornell University

Abstract

In their comment on our 2021 paper “How Green is Blue Hydrogen,” Romano et al. purport to provide “a more balanced perspective on blue hydrogen, which is in line with current best available practices.” We strongly disagree. First, we categorically dismiss their presentation on methane emissions. Methane dominates the greenhouse gas footprint of blue hydrogen in our analysis, and our estimates were based on very recent, peer-reviewed science. Romano et al., in sharp contrast, use only three sources: (1) a 2015 non-peer-reviewed report (which gave reasonable values, although at the low end, since based on older science, but nonetheless compatible with our paper); (2) a 2018 report from the International Energy Agency (which also gave values consistent with ours, but has been updated by the Agency in a 2022 report to give much higher values that are very consistent with ours); and (3) a value from a cartoon on a web site from an oil and gas industry trade group (i.e., not supported by any data or references and is simply wrong based on peer-reviewed science). We cannot stress enough that the Romano et al. criticism of our methane emission rates is based totally on this industry website cartoon. Beyond the methane issue, our analysis used actual data for capture of carbon dioxide from real-world operations. Romano et al. dismiss the use of real-world data, and instead rely on presentations from theoretical studies. We find this fanciful. But even if one accepts their theoretical values for carbon capture, the greenhouse gas footprint of blue hydrogen remains unacceptably high because of methane. We unequivocally stand by our analyses and conclusions: There is no room for blue hydrogen in a decarbonized energy future. The Romano et al. result derives from a cartoon and hypothetical guesses, not scientific data.

KEYWORDS

hydrogen, life cycle analysis

1 | INTRODUCTION

Globally, 96% of hydrogen is made from fossil fuels, almost entirely from natural gas in the United States and Europe.¹ Steam methane reforming (SMR) is overwhelmingly the dominant process for making hydrogen from

natural gas and constitutes almost 75% of all hydrogen production globally.² Natural gas is mostly methane (CH₄), and this methane is the feedstock for the SMR process. Under high pressure and temperature and with the addition of steam, CH₄ is converted into hydrogen and carbon dioxide (CO₂), with some intermediate steps.

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In addition to serving as the feedstock, natural gas is burned to create the heat and high pressure that drive SMR. Greenhouse gas emissions are high.^{3,4} Blue hydrogen is a new concept in which an effort is made to capture CO₂ emissions from the traditional SMR process. To date, blue hydrogen has been produced in only two commercial facilities globally. The oil and gas industry heavily promotes blue hydrogen, often stating it has low or zero greenhouse gas emissions.^{3,5,6} In Howarth and Jacobson,⁷ we investigated this claim and provided one of the very few peer-reviewed analyses of greenhouse gas emissions from either blue hydrogen or the traditional “gray” hydrogen made by SMR, including fully accounting for CH₄ emissions in the greenhouse gas footprints. We demonstrated that while CO₂ emissions from blue hydrogen are somewhat less than for gray hydrogen, they are still substantial, and CH₄ emissions are in fact higher due to an increased use of natural gas to power the carbon capture. These results apply even before considering the leakage rate of captured carbon dioxide. Three major uncertainties arise in calculating the potential climate forcing of blue hydrogen: (1) the emission rate of CH₄ during the extraction, piping, processing, storing, and use of natural gas; (2) the emission rate of CO₂ due to the inefficiency of carbon capture equipment and due to the fact that additional energy is needed to run carbon capture equipment and to pipe CO₂, so more natural gas is burned, emitting more CO₂; and (3) the relevant time frame for looking at climate impacts, 20 or 100 years. In their comment, Romano et al.⁸ mistakenly criticize our assumptions in the first of these two areas and inappropriately emphasize the 100 year time frame. Below, we respond to these misplaced criticisms one at a time.

2 | METHANE EMISSIONS

A majority of the total greenhouse gas emissions from producing blue hydrogen come from emissions of unburned CH₄ associated with using natural gas, according to Howarth and Jacobson.⁷ Natural gas is composed mostly of CH₄, and it simply is not possible to develop, process, store, and transport natural gas without some CH₄ being emitted to the atmosphere. Some of these emissions are due to leaks, but significant emissions also result from the routine, purposeful operations of the natural gas industry.^{9–11} For instance, for safety reasons the gas in high-pressure gas pipelines is released to the atmosphere before maintenance is performed on the pipelines. These emissions matter, since CH₄ is more than 100 times more powerful than CO₂ as an agent of global warming for the time both

gases are in the atmosphere.¹² In the 2021 AR6 Working Group No. 1 synthesis report, the Intergovernmental Panel on Climate Change (IPCC) concluded that of all human-caused warming over the past century, the contribution of CH₄ is equal to 67% of that of CO₂, 0.5°C compared to 0.75°C.¹³

To estimate CH₄ emissions in Howarth and Jacobson,⁷ we relied on the preponderance of the peer-reviewed literature, including very recent data in this rapidly growing area of science. We used a baseline estimate of 3.5% of gas consumption in our analysis, but also explored values as low as 1.54% and as high as 4.3%. Note that there has been an explosion in the number of new studies on CH₄ emissions from the natural gas industry over the past decade, with more than 1700 papers published over the past decade. Our 3.5% baseline estimate is based largely on 20 studies reported in 12 peer-reviewed papers for emissions as estimated from airplane flyovers and satellite data in North America between 2013 and 2020 (“top-down” estimates)¹⁰ and a global estimate based on trends in the 13-C stable isotopic composition of atmospheric CH₄ since 2005.¹⁴ A recent study using satellite data to examine CH₄ emissions from two of the world’s largest natural gas fields, in Turkmenistan, show a rate of 4.1%, even higher than estimates based on North American data.¹⁵ Our 4.3% estimate was based on the higher possible range calculated from the global trend in the 13-C stable isotopic composition of methane.¹⁴ The two lower values we used, 2.54% and 1.54%, are in fact lower than we believe are representative for global average emissions but nonetheless come from solid, peer-reviewed studies.^{11,16} We strongly believe that an estimate of 3.5% of gas consumption is a reasonable (probably conservatively low) average estimate for CH₄ emissions from natural gas production and use not only in the United States but globally. This was our default estimate in Howarth and Jacobson,⁷ and we stand by it.

Romano et al.’s⁸ estimates, on the other hand, are based on two out-of-date, non-peer-reviewed reports and a cartoon on a web page from the oil and gas industry. Of these, only the industry’s cartoon gives methane emissions below the range we used in our Howarth and Jacobson analysis. Specifically, Romano et al. used:

1. A non-peer-reviewed literature review written in 2015 by the Sustainable Gas Institute at Imperial College.¹⁷ This review reported a mean emission estimate of 2.2% from the studies they included. Despite the insinuation of the Romano et al. comment, this is well within the range we evaluated for the sensitivity analyses in our paper (1.5%–4.3%). Nonetheless, we firmly believe our baseline estimate of 3.5% better

represents global average emissions, since it is based on more data and more recently collected data.¹⁰

2. A 2018 report from the International Energy Agency (IEA).¹⁸ Romano et al. interpret this report as indicating CH₄ emission rates in the range of 1.4%–2%. Again, despite the insinuation of Romano et al., this range is hardly inconsistent with our range of 1.5%–4.3%. Further, the IEA has recently issued a new report, correcting their earlier estimates used by Romano et al. The new IEA report from 2022 states that “methane emissions from the energy sector are about 70% higher than reported in official data” upon which their 2018 report relied.¹⁸ Correcting the IEA numbers from 2018 used by Romano et al. (1.4%–2%) by this 70% factor increases the emission estimates to 2.4%–3.4%, which is very much in line with the range we used in Howarth and Jacobson (again, 1.5%–4.3%).
3. A value of 0.2% from a trade group of the oil and gas industry.¹⁹ The citation provided by Romano et al. is simply a web site with just a few pages, and the 0.2% value comes from a cartoon that presents an industry “emission target for 2025,” with no supporting data or references. We find it amazing that Romano et al. rely so heavily on this value in their criticism, as it is the only one in their comment that is below the range we used in Howarth and Jacobson. The 0.2% estimate is simply not believable, is not supported by verifiable data, and is very much at odds with almost all peer-reviewed studies on this topic.¹⁰

3 | CARBON DIOXIDE CAPTURE AND EMISSIONS

In their comment, Romano et al. state “a detailed reading of the paper (Howarth and Jacobson) reveals that the conclusions are inaccurate, as they were derived using an oversimplified method and a selective set of assumptions that are not representative of the technology performance and best available practices now, and especially when working in future low-carbon scenarios.”⁸ We reject this statement and conclude the opposite; namely Romano et al. have not carried out due diligence by using real-world data. In Howarth and Jacobson, we used the best available data for real-world performance, and explained the choices made in using these data. See sections 3.1 and 3.2 in our original paper.⁷ Further, our sensitivity analyses included capture rates of 90% for CO₂ both from the steam CH₄ reforming process and from the combustion of natural gas used to drive the process, values that are higher than have ever been demonstrated in commercial plants. Even under these optimistic assumptions, blue hydrogen has a greenhouse gas

footprint, larger than that from just burning natural gas (see table 2 of Howarth and Jacobson).⁷

Romano et al.⁸ reject the use of data from real-world plants, stating “the regulatory and market conditions have not been sufficiently demanding to favor the deployment of commercial hydrogen plants with high CO₂ capture rate at scale yet.” This admission is in contradiction to the claims often made by industry that blue hydrogen already has low or near-zero emissions of CO₂.^{3,5} After dismissing the value of data from real-world facilities, Romano et al. proceed to rely on hypothetical calculations for energy use and emissions, including some highly optimistic assumptions. Specifically, they use estimates for two blue hydrogen “plants,” which are so far just theoretical constructs, not physical realities subject to real-world, perhaps unexpected difficulties. To briefly summarize these two “plants:”

1. One is assumed to use conventional SMR, with an assumed postcombustion CO₂ efficiency of 90%. Romano et al.⁸ state “Thanks to heat recovery, a small increase of natural gas input (+10% compared to the corresponding gray H₂ plant) is needed to self-produce the energy for CO₂ capture and compression, resulting in a blue hydrogen plant which is effectively electrically neutral.”
2. The other is a “blue hydrogen plant based on an oxygen-blown autothermal reformer (ATR) and CO₂ capture from syngas with the methyl diethanoamine (MDEA) process, as proposed by Antonini et al.” Antonini is the second author of the Romano et al. comment on our paper. Romano et al. state “In this plant, a target CO₂ separation efficiency of 98% was assumed in the MDEA unit, resulting in overall carbon capture rate of around 93%.”⁸

Both of these case studies use highly optimistic assumptions not justified by real technologies operating continuously for one or multiple years. Whereas it is known that full-load capture rates can reach 90% or more, real carbon capture projects (e.g., Petra Nova, Boundary Dam, Gorgon) have capture rates ranging from 20% to 72% over multiple years due to equipment downtime, lack of demand for CO₂, or lower efficiency than expected.^{20–23} Note that in Howarth and Jacobson, we presented this range as 55%–72% and used a value of 65% as our default. The low value of 20% we include here is from the very poor performance of the Gorgon facility.²³ For more on problems with carbon capture in real-world facilities, see the December 2021 report from the US Government Accountability Office.²⁴ Thus, the “assumed post-combustion CO₂ capture efficiency of 90%” used by Romano et al. in their Case no. 1 is too

high, given real-world data. Further, as far as we are aware, the use of heat recovery to power the CO₂ capture in Case no. 1 has not even been tested experimentally, let alone used in commercial operation.

Regarding Case no. 2, as far as we are aware, blue hydrogen based on ATR has never been attempted in commercial operation.²⁵ Romano et al. give no examples of actual commercial efforts to use ATR, and Kim et al.²⁶ note in a 2021 paper that the required need for pure oxygen has been an impediment to ATR use by industry. The “overall carbon capture rate of around 93%” used by Romano et al., then, is hypothetical and dependent upon the 98% efficiency that they “assumed in the MDEA unit,” which has not been tested in any actual plant. Further, it is important to note that ATR produces less hydrogen per input of methane from natural gas than does SMR, and so at least 38% more natural gas feedstock is required for ATR.²⁷ This of course leads to greater methane emissions from the production, processing, storage, and transport of the needed natural gas, a fact apparently not included in the analysis of Romano et al.⁸

In support of their optimism on high efficiencies for carbon capture, Romano et al. write “As for CO₂ capture from flue gas, even though commercially immature at large scale, there is scientific and technical evidence that CO₂ capture efficiencies higher than 90% can be achieved in commercial plants. For example, the 240 MWe Petra Nova plant captured 92.4% of the CO₂ from the processed flue gas when operating at full load.”⁸ Note that we discussed this plant in Howarth and Jacobson, stating “that efficiencies of up to 90% have been observed in one of the plants when running at full load. However, this does not reflect long-term performance, which is evaluated at average load.”⁷ Our use of “a value of 65% capture efficiency from flue gases for our baseline analysis” was based in part on the data from this Petra Nova plant, viewed in its entirety. Romano should also have noted that Petra Nova shut down in 2020 because it was an economic failure, as noted in a recent report from the US Government Accountability Office.²⁴

Romano et al. further write “Also, in the recent post-combustion carbon dioxide capture Best Available Techniques (BAT) UK guidelines, 95% of CO₂ capture efficiency is targeted. Therefore, under proper economic (i.e., sufficiently high CO₂ emission cost) and regulatory conditions (e.g., cap on specific emissions), it is reasonable to assume that CO₂ capture efficiencies well above 90% can be achieved in future blue hydrogen plants.”⁸ Reaching the UK BAT guidelines seems unlikely, based on real-world experience. Regardless, the BAT guidelines are not evidence that this high efficiency can be achieved by blue hydrogen plants.

4 | GLOBAL WARMING POTENTIAL

CH₄ is a far more potent greenhouse gas than CO₂, but its residence time in the atmosphere is less. Consequently, one must define a time frame of interest to directly compare the warming influences of the two gases. Damaging climate impacts are occurring today over periods of only a few years, and short-lived powerful global warming agents such as black carbon, CH₄, and tropospheric ozone cause much more damage over the short term than over the long term. As such, from a policy and damage-control point of view, it is crucial to eliminate substances (black carbon, CH₄, tropospheric ozone) whose control can avoid catastrophic short-term damage to the climate. With that in mind, the use of a 20-year time frame for developing policies is far more useful than the use of a 100-year time frame for analyzing the impacts of blue hydrogen.^{9,28}

In Howarth and Jacobson,⁷ we used 20 years as the default. However, we also included the use of a 100-year global warming potential in our sensitivity analyses (see table in Howarth and Jacobson). Even under the 100-year assumption, the greenhouse gas emissions from blue hydrogen were still worse than or no better than those from simply burning natural gas. In their comment, Romano et al. use both 20- and 100-year global warming potentials but fail to emphasize the superiority of the 20-year time frame for avoiding immediate damage and tipping points for more severe long-term damage. Along those lines, Abernethy and Jackson²⁹ in a new 2022 paper have demonstrated that the use of a 100-year GWP is simply not compatible with reaching the climate goals set by the COP21 Paris accords in 2015.

5 | SUMMARY AND CONCLUSIONS

Nothing presented in the comment by Romano et al. has caused us to reconsider our original approach, calculations, and conclusions. Their assumptions regarding high efficiency of capture of CO₂, with very low inputs of energy, are not supported by real-world data. However, even if we fully accept the hypothetical analyses upon which they rely for carbon capture and energy requirements for blue hydrogen, greenhouse gas emissions of CH₄ will remain high. Romano et al. considered three levels of CH₄ emissions: 0.2%, 1%, and 3.5%. The two lower levels are simply not compatible with the large and growing body of literature on emissions from the natural gas industry, and in fact are lower than the range of estimates provided in the two reports Romano et al.

relied upon.^{17,30} Their sole justification for using these lower values is a number on the cartoon on a web site for an oil and gas industry trade group.¹⁹ Consequently, figures 1C, 1D, 1E, and 1F in the Romano et al. comment should be ignored. Their figures 1A and 1B, which are based on a 3.5% CH₄ emission rate using 20- and 100-year global warming potentials, demonstrate substantial greenhouse gas emissions from blue hydrogen, even under their extremely optimistic assumptions, because of the CH₄ emissions inherent in using natural gas. Similarly, the emissions shown in their figure 2 are incompatible with a decarbonized future, given the reality of CH₄ emissions, even if their technical optimism on carbon capture at low energy cost could be achieved: at a 3.5% CH₄ emission rate and 20-year global warming potential, they estimate only a 25% reduction in total greenhouse gas emissions relative to simply burning natural gas (figure 2A).⁸

We urge our engineering and science colleagues to take great care in communicating their work on greenhouse gas emissions from the production and use of hydrogen. The public and decision makers can be easily confused on these emissions, particularly in a world where the oil and gas industry is heavily engaged at messaging approaches that may be designed primarily to support their business model: to continue to sell natural gas.^{31,32} Hypothetical projections of what might be possible should not be confused with what will occur in the actual world. And while we see a future for green hydrogen (hydrogen from electrolysis of 100% renewable electricity) in a decarbonized future, the greenhouse gas emissions from blue hydrogen are unacceptably high.

In their introduction to their comment, Romano et al.⁸ said “Controversial statements from scientists at renowned institutions attract attention, irrespective of their basis in scientific facts or the rigor of the underpinning study.” They proceeded to highlight the following set of quotes from our paper:

1. “There really is no role for blue hydrogen in a carbon-free future.”
2. “There is no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat.”
3. “...blue hydrogen...is best viewed as a distraction...”
4. “There is no way that blue hydrogen can be considered ‘green’.”

We do not accept that our paper made “controversial statements,” nor that our work lacked rigor. And we stand by these quotes selected by Romano et al. which are, in fact, supported by the best available scientific data

as presented in our paper. There is nothing green about blue hydrogen.

ACKNOWLEDGEMENTS

This study is supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to Cornell University that supports Robert Howarth.

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How to cite this article: Howarth RW, Jacobson MZ. Reply to comment on "How Green is Blue Hydrogen?". *Energy Sci Eng*. 2022;10:1955-1960. doi:10.1002/ese3.1154