Putting the Howarth & Jacobson Hydrogen Paper in Context:
Decarbonization and the Potential Greenhouse Gas Emissions Performance of "Blue" Hydrogen

A recent paper by Robert Howarth & Mark Jacobson ("H&J") asks whether "blue" hydrogen (that is, hydrogen produced by reforming natural gas, with carbon capture) can be a viable low carbon fuel option and concludes that "the use of blue hydrogen appears difficult to justify on climate grounds". CATF's initial review of the paper and its context suggests otherwise. It appears to us that the paper includes several poor assumptions, is out of line with other analyses, and does not reflect the true value blue hydrogen could have for decarbonization. In fact, we estimate that blue hydrogen could deliver energy to end-users with around 80% less greenhouse gas emissions than direct use of natural gas in the near-term and even less over time. Over-reliance on the conclusions of the H&J paper in policy considerations therefore is ill-advised and is in fact a risk to successful climate mitigation.

The conclusions of the H&J paper are driven by a combination of factors including low assumed rates of carbon capture on the natural gas reforming plants that would make blue hydrogen, high assumed energy consumption to operate those carbon capture plants, and an assumption that methane emissions in the natural gas supply chain are both high today and not susceptible to reductions over time. We certainly agree with H&J that methane emissions are high today, are a key driver of climate change, especially in the short term, and must be reduced rapidly and substantially to protect the climate. We believe those methane emission reductions are imperative regardless of the future of hydrogen production technologies, however, and that deep reductions are in fact feasible in the right regulatory and/or market settings.

Our review suggests that even the most optimistic analytical case of H&J may significantly over-estimate the climate impact of future blue hydrogen relative to other researchers. The most optimistic carbon capture case in H&J, for example, coupled with their base case assumptions for methane leaks, results in a greenhouse gas (GHG) impact for blue hydrogen of 132 grams CO2-equivalent per million Joules of gross fuel heat delivered (which we write as 132 gCO2e/MJ-HHV). In contrast, the peer-reviewed research of Antonini et al published by the Royal Society of Chemistry in 2020, which includes both upstream methane emissions and direct emissions from hydrogen production, suggests around 47 gCO2e/MJ-HHV when adjusted to a 20-year Global Warming Potential (GWP) basis like H&J. Antonini et al conclude that *"reforming-based hydrogen with CCS must be considered as a clean energy carrier in any successful decarbonisation scenario"*.

Our analysis and interpretations of these studies and their context is described here:

- **Numerous analysts including IEA have concluded that hydrogen will be needed to decarbonize parts of the global economy where electrification cannot easily replace fossil fuels.** Bloomberg New Energy Finance estimates that with strong policy, hydrogen could provide 24% of final energy globally in a 1.5°C decarbonization scenario, still representing only half of total "unlikely-to-electrify" demand. The recent IEA Net-Zero by 2050 report estimates that even in a fully decarbonized world, by 2050 electricity may provide only 44% of transport sector energy, and 46% of industrial sector energy. The American Council for an Energy Efficient Economy estimates that to support decarbonization 36% of the energy for industrial high temperature processes and 35% of the energy for long-distance planes in the US may need to come from zero-carbon fuels like hydrogen, while Agora Energiewende indicates that in Germany hydrogen could play a key role in electricity generation to balance renewables, in industry, and in freight transport. Hydrogen and other fuels derived from hydrogen are understood to be a key tool for decarbonization. Without this hydrogen available, we likely will not meet climate targets.

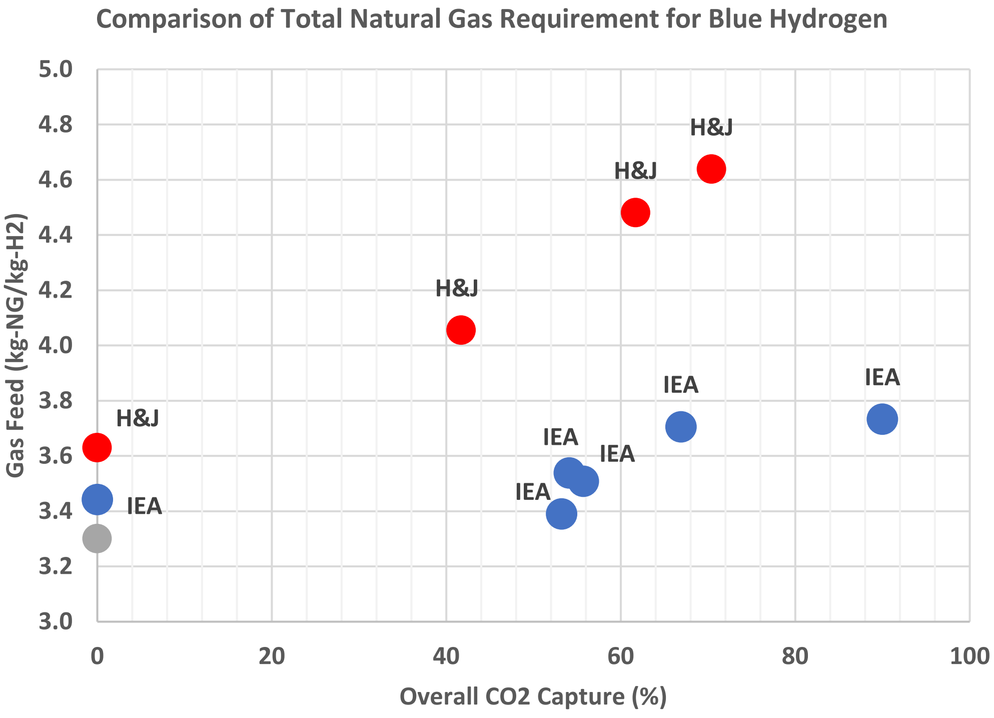
- **The framework of the H&J paper appears to assume incorrectly that blue hydrogen and green hydrogen are competing alternatives.** Analysis by IEA and others suggests that to achieve decarbonization by mid-century we could well need both. The IEA estimates that although 62% of the required hydrogen for 2050 decarbonization will be "green" (that is, produced by water electrolysis with clean electricity), an additional 38% will be required from fossil fuels with carbon capture. This is driven, in part, by the rapid and massive scale needed to supply low carbon energy options for "hard to abate" sectors, including shipping, trucking, grid balancing, and industrial sources. Including blue hydrogen in the supply mix provides an additional source of supply so that clean electricity can be used directly where it is required most, especially in the near term. Blue hydrogen also is lower cost than green in many regions, at least in the near term, allowing critical decarbonization funds to be spent elsewhere (e.g., other low-carbon infrastructure), and blue hydrogen could alleviate some constraints on fuel production arising from land-use conflicts.

- **The methane loss rates assumed in the H&J paper are higher than those in the literature**.
    - H&J use a 3.5% leak rate, largely based on "in press" analysis by the first author that is not available for review at present. H&J also increase the leak rate they use by including a high estimate of emissions from natural gas distribution, which is not relevant to blue hydrogen production since reformers generally would receive natural gas directly from transmission lines, not via a distribution system. (H&J mischaracterize the measurement of distribution emissions they cite as a study of "gas transport and storage"). In contrast to H&J's high leak rate, the best peer-reviewed analysis available as of now estimates that the US leak rate is about 2.3%. Notably, a portion of these emissions are from operations that are economically focused on oil production, not gas production. In any case, it is important to note that the current leak rate can and must be made much lower. For example, the gas production region of northeast Pennsylvania has a measured leak rate of 0.3-0.4% (see fig 5 here).

    - Methane abatement through regulation is in process in the US, Europe, and elsewhere. It has been documented that it is feasible, based on regulations already on the books in leading states, to reduce oil and gas methane emissions by 65% in a matter of a few years. The oil and gas industry is publicly targeting a leak rate of 0.2%.

Just accounting for leak rates based on current measurements, and leak rates possible with feasible methane mitigation, creates a huge difference in the overall GHG footprint of hydrogen produced from natural gas. Finalizing regulations to limit all methane emissions from the oil and gas sector is critical and urgent, as underscored by the most recent IPCC report. And doing so will also address one of the most significant potential contributors to the climate footprint of blue hydrogen.

- **The carbon capture assumptions in the paper do not reflect likely capability of future blue hydrogen production projects, resulting in significantly overstated CO2 releases.**
    - The carbon capture levels are too low. H&J's best carbon capture sensitivity case only assumes capture of about 70% of the overall CO2 from a natural gas reforming process. In contrast, current project proposals in the UK, Netherlands, and Canada as well as development in the US will employ levels of 90% or more and in some cases 95-98%. These projects with high capture levels include auto-thermal reforming ("ATR") technologies with pre-combustion capture capture and more conventional steam methane reforming ("SMR") technologies with post-combustion carbon capture applied to the plants. More than 92% CO2 removal from flue gas and more than 93% CO2 removal from synthesis gas have been demonstrated in practice with commercial technology, with significantly higher levels possible.
    - The energy assumed by H&J to operate carbon capture is too high. To capture CO2 from process and flue gas H&J assumes an energy penalty significantly higher than standard estimates. As a result, the authors overstate the amount of fuel needed for carbon capture. In the figure below we have compared the total amount of natural gas required for each unit of hydrogen produced in the H&J paper with the results of detailed expert analysis by IEA for a range of carbon capture levels and plant configurations. The H&J natural gas requirements are substantially higher than estimated by specialists in the field. As a result, H&J overstate the amount of fuel needed for carbon capture, increasing both direct CO2 emissions and upstream methane emissions in the natural gas supply chain. Notably, H&J perform no sensitivity analyses on their assumption of how much energy is required for carbon capture or various reforming process configurations.



Notes to figure: 1) H&J used simplified feed gas of 100% methane whereas IEA cases represent a more typical natural gas blend (still mostly methane but including some ethane and other gases), which increases H&J gas feed slightly versus IEA; 2) figures for H&J

derived here using total gas feed in their Table 1 and 1.0 MJ (HHV) hydrogen production in each case (equivalent to 7.05 g hydrogen), except for the case at ~70% overall carbon capture which was derived by CATF from data in H&J, reflecting 7.11 g CH4/MJ-HHV-H2, but not presented by them directly in their Table 1; 3) Most IEA cases include a small net electricity export to grid, which is excluded here as H&J do not specify net electric balance in their analysis; including a credit for net electricity export would reduce the effective natural gas feed for most of the IEA cases slightly, especially the 0% carbon capture case; the grey dot in the figure represents this impact, assuming export power from the reforming plant site offsets 0.13 tonne of natural gas per MWh of electricity exported, following US DOE studies of new natural gas combined cycle plants.

  - The scenarios considered by H&J do not capture CO2 from energy assumed to drive the capture unit. This decision, combined with overestimating carbon capture's energy needs, results in extremely high CO2 emissions from operating the capture equipment. These fuel emissions rival those from the SMR process in the central case. The impacts of this issue are further addressed below.

- **In total, the overall greenhouse gas emissions of blue hydrogen estimated by H&J are significantly higher than those of other researchers.** The ATR cases of Antonini et al utilize carbon capture ranging from 90%-98%+. These are summarized in the three rightmost columns in their figure below, with average GHG emission of around 23 gCO2e/MJ-LHV (where we have used LHV to denote that the values for hydrogen in Antonini et at are on a lower heating value basis). Of that total, on average around 13 gCO2e/MJ-LHV are due to the fuel supply chain. Those results are based on 100-year GWP. If we assume that all of the fuel supply chain emissions are methane (which will overstate methane impacts), and increase those to a 20-year GWP (multiplying by the ratio of GWPs 86/25 = 3.44), and also adjust to a gross (higher) heating value basis for hydrogen as used in H&J, the fuel supply chain emissions increase to around 38 gCO2e/MJ-HHV, and the average total hydrogen production emissions increase to about 46 gCO2e/MJ-HHV.

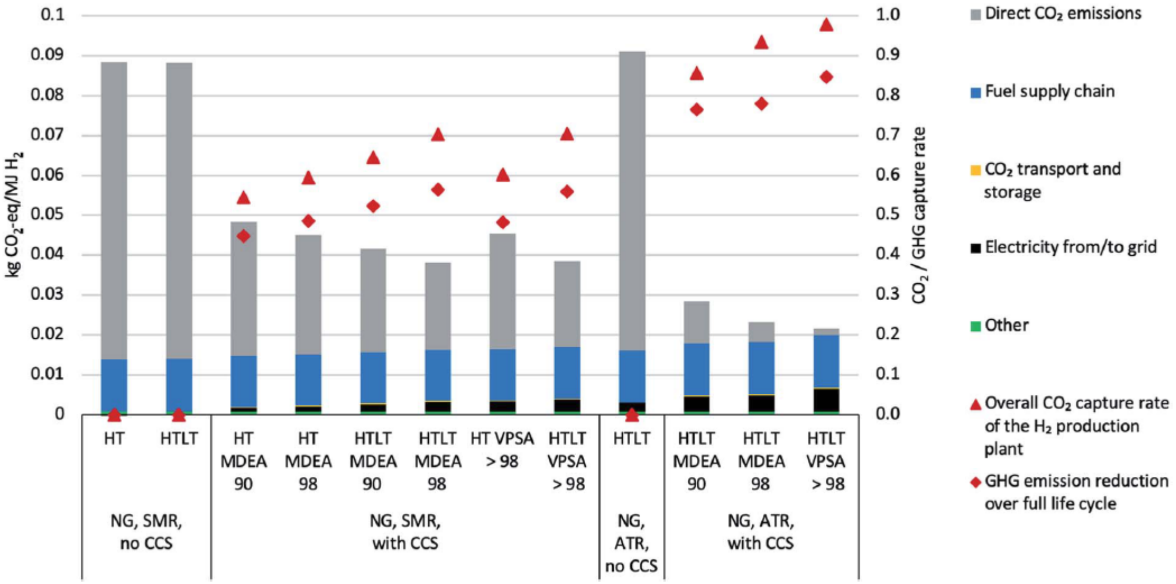
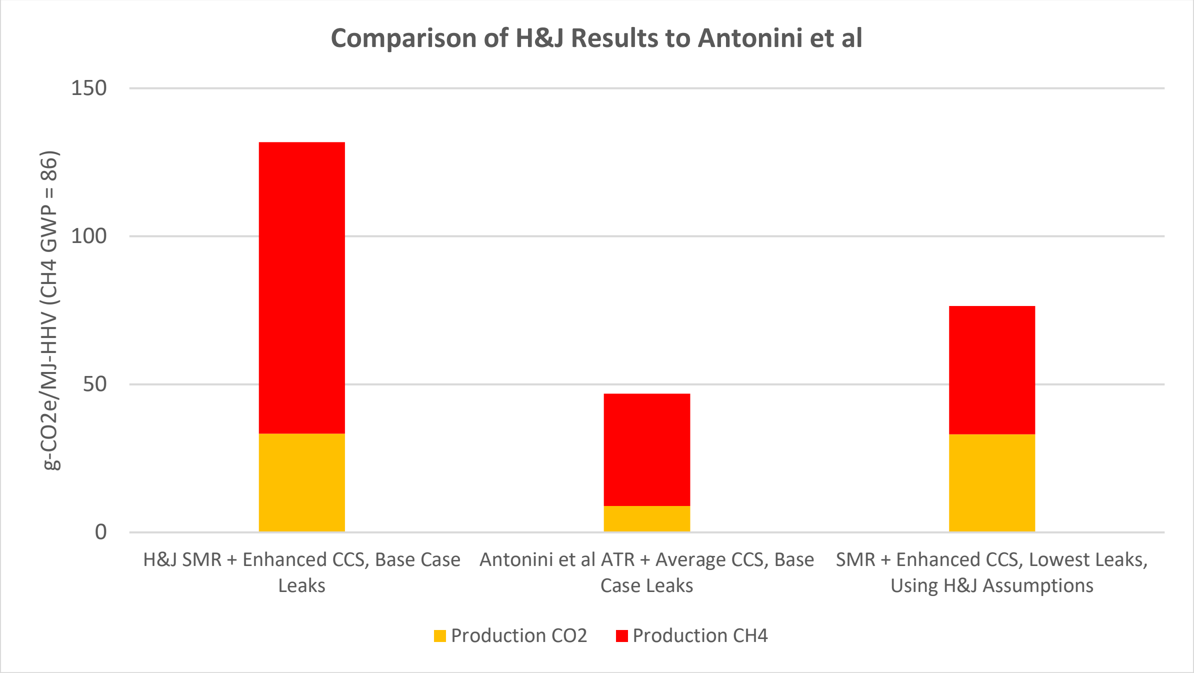


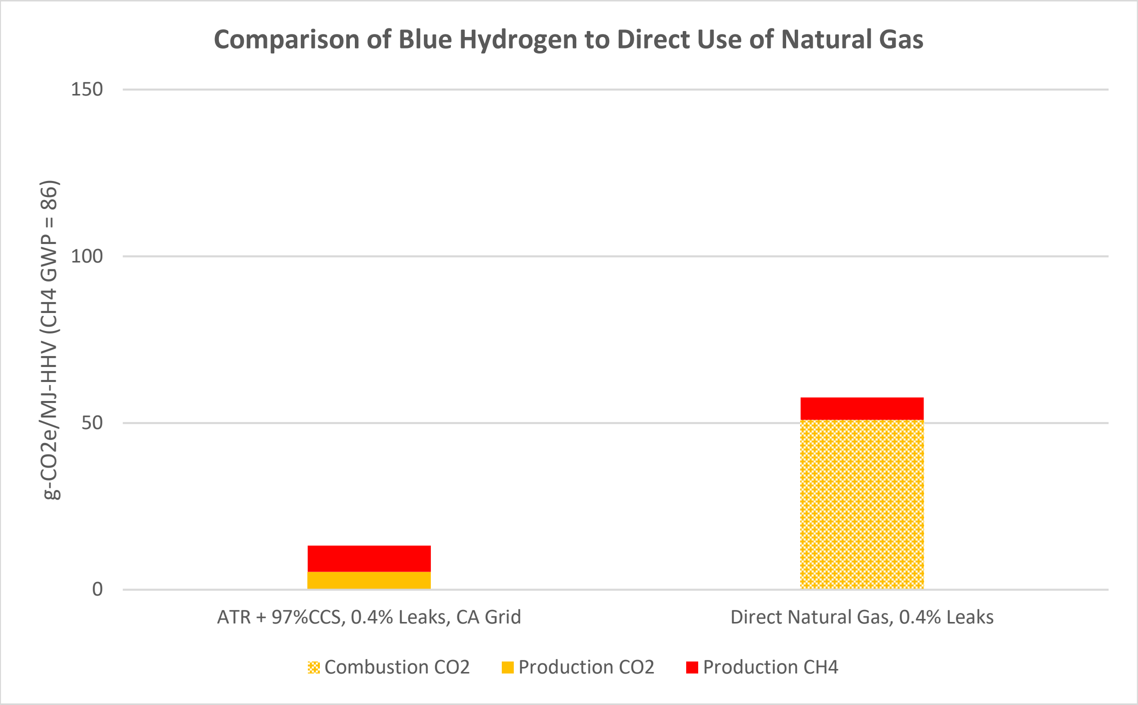
Fig. 4 Life cycle impacts on climate change of H_2 production with natural gas (NG) with various reformer plant configurations with and without CCS. The left *y*-axis shows kg of CO_2-equivalents per MJ H_2 produced, while the right *y*-axis shows the overall CO_2 or greenhouse gases (GHG) capture rate. The category "Other" includes "H_2 production unit infrastructure", "Catalysts&Adsorbents", "Direct emissions from fuel combustion in furnace", and "Water supply".

For comparison, the best H&J carbon capture case applies 90% CO2 removal on both reformer process gas and reformer furnace flue gas, but no capture of CO2 resulting from energy needed to drive the carbon capture process itself, resulting in around70% carbon capture overall in their analysis. For clarity we label that H&J case "Enhanced CCS" here although much higher levels are possible. Combined with their base case methane leak rate assumption of 3.5%, this case results in about 132 gCO2e/MJ-HHV hydrogen, nearly a factor of 3 higher than Antonini et al. This comparison is summarized in the figure below.



Although H&J do not include a sensitivity case in their tabulated results that combines their Enhanced CCS with their most optimistic methane leak rate assumption of 1.54%, we have estimated that case using their tabulated information for other cases and included it in the comparison figure above. For this case in the H&J analysis there would be about 77 gCO2e/MJ-HHV. This is still more than 60% greater than the average Antonini et al results for ATR with carbon capture, after adjusting Antonini et al's upstream methane emissions to reflect a 20-year GWP of 86.

- **Natural gas reforming with deep carbon capture, coupled with significant reductions in natural gas supply chain methane emissions, can produce a low-carbon hydrogen product.** Our analysis indicates that ATR with 97% carbon capture is technically feasible and available for early deployment and could result in greenhouse gas emissions of about 0.8 kg CO2 per kg of hydrogen produced, equivalent to about 5.6 gCO2e/MJ-HHV, when using electricity with a carbon intensity of the California grid to power internal auxiliary loads. Because an ATR with this level of carbon capture would consume around 3.2 kg of natural gas for each kg of hydrogen produced, methane leaks of 0.4% in the fuel supply chain would increase the GHG emissions for the hydrogen by around 7.9 gCO2e/MJ-HHV more, using a 20-year methane GWP, resulting in a total of around 13 gCO2e/MJ-HHV (equivalent to 1.9 kgCO2e/kg-H2). Although not a full lifecycle analysis, this is approximately a 77% reduction in CO2e per unit of gross delivered fuel heat compared to burning natural gas directly, assuming the same reduction in methane leaks for the direct natural gas pathway as we apply for the hydrogen pathway. Our results are summarized in the figure below.



- **NGO research in Canada aligns well with the Antonini et al results.** The Pembina Institute in Canada recently published a description of blue hydrogen production technologies and assessed their carbon emissions intensity. Similar to Antonini et al, upstream methane emissions were included as well as cases for solar, wind, and hydro power for electrolysis. The Pembina results are quite similar to the Antonini et al estimates. (When comparing figures note that 20 kg per GJ is the same as 0.02 kg per MJ).

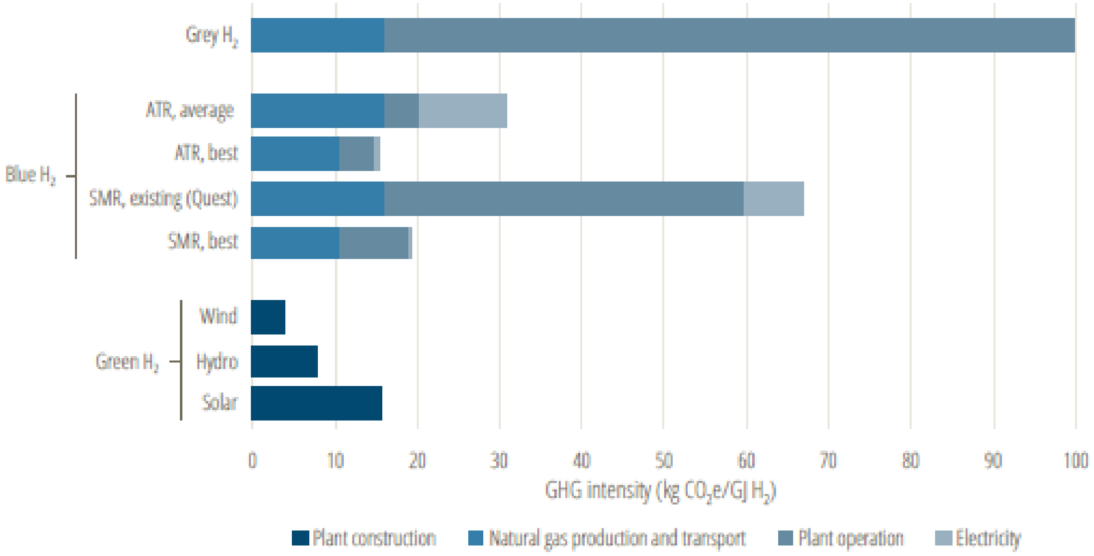


Figure 3. Life cycle carbon intensity of hydrogen production

Based on the above, we conclude that if substantial reductions in methane leaks are ensured, and efficient reforming processes with high levels of CO2 removal are used, “blue” hydrogen can in fact make a contribution to preventing climate change. While it is important to emphasize the need to ensure low carbon energy sources are in fact low carbon, it is extremely risky to the climate to prematurely cut off important solution pathways given the enormous challenge we face in decarbonizing our global energy system.