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COMMENTARY

Comment on "How green is blue hydrogen?"

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Abstract

This paper is written in response to the paper "How green is blue hydrogen?" by R. W. Howarth and M. Z. Jacobson. It aims at highlighting and discussing the

The authors of the article "Comment on "How green is blue hydrogen?", published on March 29th 2022 requested that the journal update the Conflict of Interest statement originally published with the article. The Conflict of Interest statement has now been updated to correct the unapproved version mistakenly published by the editors with the original version of the article."

method and assumptions of that paper, and thereby providing a more balanced perspective on blue hydrogen, which is in line with current best available practices and future plant specifications aiming at low CO_2 emissions. More specifically, in this paper, we show that: (i) the simplified method that Howarth and Jacobson used to compute the energy balance of blue hydrogen plants leads to significant overestimation of CO_2 emissions and natural gas (NG) consumption and (ii) the assumed methane leakage rate is at the high end of the estimated emissions from current NG production in the United States and cannot be considered representative of all-NG and blue hydrogen value chains globally. By starting from the detailed and rigorously calculated mass and energy balances of two blue hydrogen plants in the literature, we show the impact that methane leakage rate has on the equivalent CO_2 emissions of blue hydrogen. On the basis of our analysis, we show that it is possible for blue hydrogen to have significantly lower equivalent CO_2 emissions than the direct use of NG, provided that hydrogen production processes and CO_2 capture technologies are implemented that ensure a high CO_2 capture rate, preferably above 90%, and a low-emission NG supply chain.

KEYWORDS
carbon capture, CCS, hydrogen, natural gas

1 | INTRODUCTION

Controversial statements from scientists at renowned institutions attract attention, irrespective of their basis in scientific facts or the rigor of the underpinning study. So, it was with a recent paper on hydrogen from natural gas (NG) reforming with CO_2 capture and storage (*blue hydrogen*) by Howarth and Jacobson[1] (hereafter referred to as HJ) in this journal that purported to demonstrate that:

- "There really is no role for blue hydrogen in a carbon-free future."
- "There is no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat."
- "... blue hydrogen ... is best viewed as a distraction ..."
- "There is no way that blue hydrogen can be considered 'green'."

The publication has drawn a lot of attention and led to discussions in the press and amongst scientists and engineers. The media have adopted these latest "findings" as a reason to question hydrogen as a sustainable energy carrier in general.[2] However, a detailed reading of the paper 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.

The scope of this communication is to summarize the main shortcomings in the method used in the HJ study and to present a balanced perspective on blue hydrogen production. Because the regulatory and market conditions have not been sufficiently demanding to favor the deployment of commercial hydrogen plants with high CO_2 capture rate at scale yet, our analysis is based on data for simulated plants from the literature, with assumptions that represent the realistic design of plants with commercial-ready technologies, aiming at low CO_2 emissions. In this analysis, we demonstrate that blue hydrogen can have much lower greenhouse gas emissions than the direct combustion of NG.

This paper deliberately reproduces the same level of detail adopted in the original HJ paper. More accurate environmental analyses should be based on a complete Life Cycle Assessment (LCA) methodology, as for example recently published by Bauer et al.[3] Nevertheless, this simplified approach is sufficient to quantitatively describe and analyze the impacts on climate change of the main parts of the blue hydrogen value chain and is therefore suitable to provide reliable conclusions on the climate impacts of blue hydrogen.

In Section 2 we discuss blue hydrogen production before addressing fugitive methane emissions in Section 3. A discussion follows in Section 4 before we conclude in Section 5.

2 | BLUE HYDROGEN PRODUCTION

The carbon balance of a blue hydrogen production plant depends upon three main components: (i) the consumption of NG feedstock, (ii) electricity, and (iii) the CO_2 capture efficiency. In the HJ paper, the following baseline values have been taken, either as assumptions or resulting from their calculations:

1. Total methane consumption of $25.6\,g_{CH_4}/MJ_{H_2}$* for gray hydrogen (i.e., hydrogen from NG reforming without CO_2 capture) and $31.6\,g_{CH_4}/MJ_{H_2}$ for blue hydrogen† production, where the higher consumption in the blue hydrogen plant ($+6\,g_{CH_4}/MJ_{H_2}$) is due to the energy (electricity and heat) needed to run the CO_2 capture plant.
2. A CO_2 capture rate of 85% from syngas and 65%‡ from the flue gas, leading to direct CO_2 emissions from the blue hydrogen plant of $5.8 + 11.1 = 16.9\,g_{CO_2}/MJ$, compared with $70.3\,g_{CO_2}/MJ$ from a gray hydrogen plant. The assumed CO_2 capture rates derive from data from the Quest hydrogen plant[4] and from two first-of-a-kind commercial-scale postcombustion capture plants in coal power plants.[5–7] The emissions associated with energy for the CO_2 capture process are equal to $16.3\,g_{CO_2}/MJ$, estimated by assuming that the energy used in the carbon-capture process causes additional carbon dioxide emissions equal to 25%§ of the CO_2 captured from the steam reforming process and 39%‖ of the CO_2 captured from the flue gases.

In this regard, it should be noted that:

1. To accurately estimate the energy consumed in a blue hydrogen plant, heat and mass balances should be computed through process simulations (and/or measured in real-world plants designed for substantially lower CO_2 emissions, when deployed), including thermal integration and waste heat recovery. Rigorous studies in the literature[10,11] show that heat recovery is sufficient for self-generating all or the large majority of the heat and power needed to drive the CO_2 capture plant. By not considering heat recovery, the primary energy consumption of the hydrogen plant is drastically overestimated in HJ.
2. The CO_2 capture rate is taken from existing plants that are designed and operated to capture CO_2 for enhanced oil recovery. These plants do not aim to maximize CO_2 capture as there is no financial or design incentive to do so. In a CO_2-constrained future, we can reasonably expect plants to be designed to maximize CO_2 capture as far as is economically viable. Technology to separate CO_2 from syngas with an efficiency higher than 95% (passing 99% with advanced configurations) has been employed for decades in ammonia plants,[12,13] where CO_2 is separated from syngas with pressure and composition equivalent to blue hydrogen plants. As for CO_2 capture from flue gas, even though commercially immature at large scale, there is scientific and technical evidence that CO_2 capture efficiencies higher than 90% can be achieved in commercial plants. For example, the 240 MW_e Petra Nova plant captured

*Consistently with the HJ paper, combustion energy is always reported on a Higher Heating Value (HHV) basis.

†In this document, for the sake of brevity, we will only consider the blue hydrogen case that includes CO_2 capture from both the Steam Methane Reforming (SMR) syngas and the reformer flue gas, as this is the most significant case assessed by HJ in their paper.

‡HJ justify their assumption of 65% capture rate from flue gas by claiming that "[...] capture efficiencies of carbon dioxide from the exhaust stream of two coal-burning power plants are reported in the range of 55%–72%."[1] It is inappropriate to derive conclusions for the broad technology performance and emissions from first-of-a-kind or demonstration plants, where heat integration is purposely suboptimal and high overall emission reduction is not targeted. Importantly, the lowest value of 55% refers to the Petra Nova plant and derives from calculations described by Jacobson,[5] where uncaptured emissions from the cogeneration gas turbine plant installed to provide heat for solvent regeneration are included in the calculation of the capture rate. However, as the scope of Petra Nova demonstration plant was not to capture the CO_2 generated by the gas turbine but exclusively from the coal combustion flue gases, the 55% capture value is not representative of the capture rate achievable by the technology itself, especially when deployed in a different process.

§The assumed 25% value corresponds to the percent heat rate penalty due to CO_2 capture (i.e., percent increase of fuel consumption to generate a unit of electricity, which is proportional to the reverse of the electric efficiency) of a coal-fed integrated gasification combined cycle (IGCC).[8,9] This corresponds to assuming that the reduced power output from an IGCC with CO_2 capture is compensated by generating power with another IGCC without CO_2 capture. Using this value to estimate the emissions associated to CO_2 capture from syngas of an NG blue hydrogen plant is methodologically inappropriate.

‖The assumed 39% value is retrieved from CO_2 balances of the Petra Nova plant, elaborated by Jacobson,[5] reporting that $200.9\,g_{CO_2}/kWh$ are emitted from the cogeneration gas turbine used to provide heat needed to capture $516\,g_{CO_2}/kWh$ from the coal power plant flue gas. As already stated, it is inappropriate to use such data from the Petra Nova power plant, where the process was intentionally not designed to provide decarbonized energy for CO_2 capture.

92.4% of the CO_2 from the processed flue gas when operating at full load, meeting the target capture of 5200 t_{CO_2}/day.[6] Also, in the recent postcombustion carbon dioxide capture Best Available Techniques (BAT) UK guidelines, 95% of CO_2 capture efficiency is targeted.[14] Therefore, under proper economic (i.e., sufficiently high CO_2 emission cost) and regulatory conditions (e.g., cap on specific emissions), it is reasonable to assume that CO_2 capture efficiencies well above 90% can be achieved in future blue hydrogen plants, as has also been claimed in new industrial projects targeting a 95% carbon-capture rate.[15,16]

For this analysis, we compare the blue hydrogen plant with flue-gas CO_2 capture from the HJ paper with the following two plants, whose mass and energy balances have been computed with rigorous process simulations:

- A blue hydrogen plant based on conventional SMR and postcombustion CO_2 capture from the IEAGHG report.[10] This plant includes a postcombustion capture amine process with 90% CO_2 capture efficiency. Thanks to heat recovery, a small increase of NG input (+10% compared with the corresponding gray H_2 plant) is needed to self-produce the energy for CO_2 capture and compression, resulting in a blue hydrogen plant which is effectively electrically neutral. It is worth noting that the IEAGHG report was prepared by a leading engineering company, reviewed by industrial experts and includes reproducible mass and energy balances.
- A blue hydrogen plant based on an oxygen-blown autothermal reformer (ATR) and CO_2 capture from syngas with the methyl diethanoamine (MDEA) process, as proposed by Antonini et al.[11] In this plant, a target CO_2 separation efficiency of 98% was assumed in the MDEA unit, resulting in overall carbon-capture rate of around 93%, due to emissions from combustion of unconverted CO and CH_4. This plant is a net importer of electricity, mainly due to the additional consumption to produce oxygen for the ATR.

These two cases were selected because they provide detailed and rigorous publicly available information of what could be readily achieved with modern technologies in the near future. Nevertheless, plants combining different reforming and CO_2 separation processes may be designed based upon both mature (e.g., CO_2 separation processes typical of ammonia plants) and emerging technologies, which could achieve even higher overall CO_2 capture efficiencies.[16]

Table 1 compares the CO_2 balance derived by HJ with the balances from the above-mentioned studies. In the comparative analysis, indirect NG consumption and CO_2 emissions from power generation are assumed to derive from an NG combined cycle power plant with 50%$_{LHV}$ (or 45.2%$_{HHV}$) electric efficiency with 90% CO_2 capture efficiency, resulting in specific emissions of 41 kg_{CO_2}/MWh.

Table 1 shows that the assumed plant CO_2 emissions are about 4–7 times higher in HJ than in either of the comparative plants (33.2 vs. 4.6–7.0 g_{CO_2}/MJ_{H_2}), and NG consumption is also higher (+28%–38%: 1.75 vs. 1.27–1.37 MJ_{NG}/MJ_{H_2}).

3 | NG SUPPLY CHAIN FUGITIVE EMISSIONS

The NG supply chain includes exploration and production (E&P), processing, transmission, storage, and distribution, whereby direct methane emissions occur to some extent at all stages. In E&P, methane emissions occur at drilling and production installations, from leaking wells and leakages in installations, and during flaring or venting operations. Methane emissions in the processing, storage, transport, and distribution mainly come from pneumatic components (e.g., pressure regulators), from blow-off, or from unforeseen leaks.

The literature survey conducted by Balcombe et al.[17] shows that the range of estimated direct methane emissions across the supply chain is very large: from 0.2% to 10% of produced methane. According to Balcombe et al.,[17] the majority of the estimates lie between 0.5% and 3% of produced methane, with the mean across the estimates at 2.2%, and the median at 1.6%. Methane is responsible for most of the emissions in the extraction, transmission, storage, and distribution phases, whereas CO_2 dominates the processing emissions. In total, methane is responsible for around 62% of the total GHG emissions along the supply chain (using a global warming potential [GWP] for methane of 34 $kg_{CO_{2\text{-eq}}}/kg_{CH_4}$, referring to a 100-year time horizon, as discussed in the last paragraph of this section). The indirect emissions intensity of global gas production (including production, processing, and transport phases) reported in the IEA World Energy Outlook 2018[18] show that the average emissions intensity of all the sources of gas was just under 100 $kg_{CO_{2\text{-eq}}}$/boe. In most sources with total CO_2 intensity between 80 and 100 $kg_{CO_{2\text{-eq}}}$/boe, methane leakage contributed

TABLE 1 CO_2 emissions in $g_{CO_2}/MJ_{H_2\text{-HHV}}$ from the blue hydrogen plant

	HJ[1]	IEAGHG[10] (SMR with postcombustion CO_2 capture)	Antonini et al.[11] (ATR with MDEA precombustion CO_2 capture)
Feedstock[a] consumption			
Direct consumption in the SMR process, $g/MJ_{H_2}(MJ/MJ_{H_2})$	25.6 (*1.42*)	26.7 (1.37)	23.8 (1.22)
Consumption to drive the CO_2 capture unit, $g/MJ_{H_2}(MJ/MJ_{H_2})$	6.0 (*0.33*)	–[b]	–[b]
Net electricity consumption, MJ_e/MJ_{H_2}	–[c]	−0.0012	0.0217
Indirect consumption for power generation, $g/MJ_{H_2}(MJ/MJ_{H_2})$	–[c]	*−0.05* (*−0.003*)	*0.93* (*0.048*)
Total consumption in blue H_2 plant, $g/MJ_{H_2}(MJ/MJ_{H_2})$	**31.6 (*1.75*)**	***26.6 (1.37)***	***24.7 (1.27)***
CO_2 emissions			
Direct emissions from the methane fed to the reformer, g_{CO_w}/MJ_{H_2}	5.8	7.0	4.4
Emissions associated to energy for the reforming process, g_{CO_2}/MJ_{H_2}	11.1		
Emissions associated to energy for the CO_2 capture process, g_{CO_2}/MJ_{H_2}	16.3	–[b]	–[b]
Indirect emissions associated to power generation, g_{CO_2}/MJ_{H_2}	–[c]	−0.01	0.2
Total emissions from blue H_2 plant, g_{CO_2}/MJ_{H_2}	**33.2**	**7.0**	**4.6**

Note: Values in italics are derived from elaboration of the data in the references.

Abbreviations: ATR, autothermal reformer; MDEA, methyl diethanoamine; SMR, steam methane reforming.

[a]Feedstock is assumed pure methane by HJ and NG with HHV equal to 51.473 MJ/kg in IEAGHG report and by Antonini et al.

[b]Consumptions and emissions to drive the CO_2 capture unit affect the electric balance and are accounted for in the net electricity consumption.

[c]Not estimated. Indirect feedstock consumptions and emissions are estimated by assuming that the energy used in the carbon-capture process results in carbon dioxide emissions equal to 25% of the CO_2 captured from the stream reforming process (corresponding to $8.2 g_{CO_2}/MJ_{H_2}$) and 39% of the CO_2 captured from the flue gases ($8.1 g_{CO_2}/MJ_{H_2}$), leading to total emissions from energy to drive the capture process of $16.3 g_{CO_2}/MJ_{H_2}$.

with around 50-70 $kg_{CO_{2\text{-eq}}}$/boe.[¶] This corresponds to a leakage rate between 1.4% and 2.0%, which is consistent with the data from Balcombe et al.[17]

On the basis of annual data for 2020, IEA estimated that the methane emissions intensity of the NG supply chain among the worst-performing countries is more than 100 times higher than among the better ones.[19] Such a spread indicates that there is room to lower the emission intensity, as a significant part of the emissions are avoidable without needing complex measures and at a negative cost.[20] According to the IEA, "reducing methane leaks into the atmosphere is the single most important and cost-effective way for the industry to minimize overall emissions from core oil and gas operations."[21]

Methane emissions are increasingly being identified and targeted by policy makers. At COP26, over 100 countries, who collectively emit around 50% of total methane emissions, signed up to the Global Methane Pledge, which aims to reduce methane emissions by 30% by 2030 compared with 2020 levels.[22] In December 2021, the EU Commission filed a first-ever legislative proposal of regulation on methane emission reduction in the energy sector, aiming at: (i) improving the accuracy of information on the main sources of methane emissions associated with energy produced and consumed within the EU, (ii) ensuring further effective reduction of methane emissions across the energy supply chain, and (iii) improving the availability of information to provide incentives for the reduction of methane emissions related

[¶]These ranges can be retrieved from fig. 11.7 (Indirect emissions intensity of global gas production, 2017) in the IEA World Energy Outlook 2018.[18]

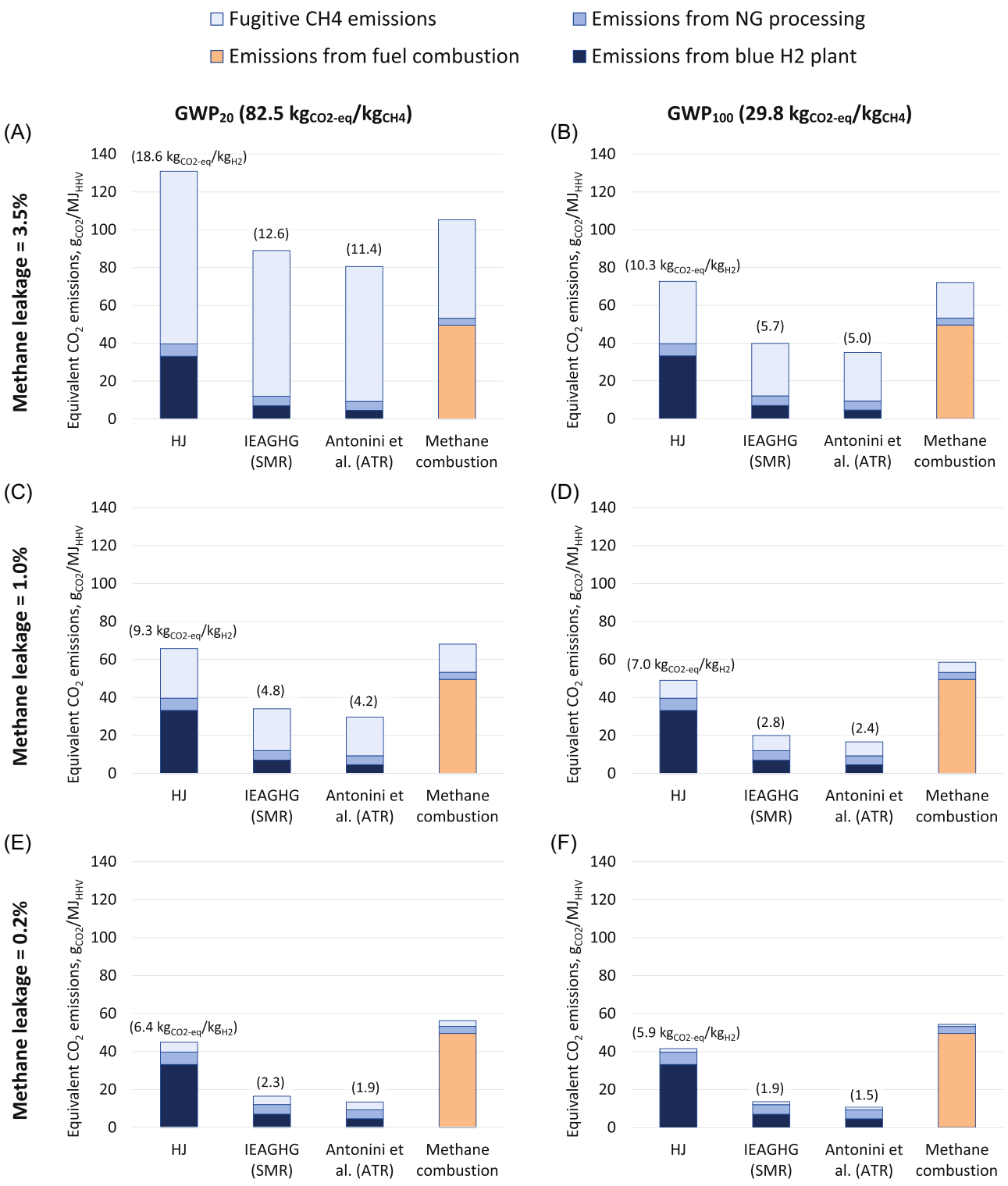

FIGURE 1 Equivalent CO_2 emissions of blue hydrogen production and methane combustion for methane GWP_{20} (A,C,E) and GWP_{100} (B,D,F) and methane leakage rates of 3.5% (A,B), 1% (C,D), and 0.2% (E,F). ATR, autothermal reformer; GWP, global warming potential; HJ, Howarth and Jacobson; SMR, steam methane reforming

to fossil energy imported to the EU.[23] Progress has also been demonstrated by the Oil and Gas Climate Initiative (OGCI), an industry grouping representing some 30% of oil and gas production globally, who have shown that upstream methane emissions of no more than 0.2% are being achieved by their members today, targeting well below 0.2% by 2025.[24]

In the HJ paper, a baseline leakage rate of 3.4% has been assumed, deriving from 2.6% emissions in the production stage and 0.8% in the storage and transport of the NG to consumers. The methane leakage rate assumed by HJ for the production stage is consistent with the data from a recent study on the climate intensity of NG in the United States, where emissions from 0.9% to 3.6% of the methane withdrawn have been estimated.[25] On the other hand, additional emissions from the storage, transport, and distribution have been derived from data on urban centers along the US east coast.[26] This urban infrastructure is not relevant for blue hydrogen plants that will be connected to the NG transport grid rather than the distribution grid.

Summarizing, while CH_4 emissions along the NG supply chain are an important factor for the overall equivalent CO_2 emissions of blue hydrogen plants, the baseline leakage rate of 3.4% assumed in the HJ paper is at the high end of the estimated emissions from current NG production in the United States. This value should not be considered representative of all-NG and blue hydrogen value chains globally. The large variability of emissions from different NG value chains and the large potential in their reduction means that the climate impact of blue hydrogen plants should be evaluated on a case-by-case basis, considering the specific NG value chain associated with the plant.

An additional important aspect to address is the metric for the quantification of the climate impact of methane emissions. Although different metrics have been proposed,[27] the most widely used metric is the GWP. This metric compares the contribution of greenhouse gases to the radiative forcing of CO_2 over a time frame of typically 20 or 100 years. Most agencies and regulations[19,28–31] consider the 100-year time horizon (GWP_{100}) as the standard metric. A 1 kg of methane in the atmosphere has a GWP_{100} between 28 and 34 times higher than a kg of CO_2.[32] Due to the low lifetime of methane in the atmosphere compared with CO_2, its GWP over a 20-year time frame (GWP_{20}) is significantly higher, and the emission of 1 kg of CH_4 corresponds to 82.5–86 $kg_{CO_{2\text{-eq}}}$ under such a time frame.[32,33] We consider the two metrics equally significant and in our quantitative analysis we use GWP_{100} and GWP_{20} values of 29.8 and 82.5 $kg_{CO_{2\text{-eq}}}/kg_{CH_4}$, respectively, in agreement with the most recent IPCC Assessment Report 6.[33] These values compare well with those assumed by HJ (34 and 86 $kg_{CO_{2\text{-eq}}}/kg_{CH_4}$), who however focused their analysis on GWP_{20} as the baseline value.

4 | OVERALL EMISSIONS FROM BLUE HYDROGEN PLANTS

On the basis of the data presented in the previous sections, Figure 1 combines the GWP_{20} and GWP_{100} values of methane and leakage rates of 0.2%, 1.0%, and 3.5%. A 0.2% corresponds to a low leakage rate, representative of current low-emission value chains and the OGCI target; 3.5% represents a high leakage rate value chain, assumed as the baseline in the HJ paper. The spreadsheet used for generating the charts is available in the Supporting Information of this article.

Figure 1A shows the reference HJ scenario, with a methane leakage rate of 3.5% and GWP_{20}. In this scenario, the climate impact is largely dominated by methane leakage emissions and the HJ blue hydrogen process results in equivalent CO_2 emissions of about 131 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$ (i.e., 24% more than direct NG combustion). The emission of 135 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$ reported in the HJ paper (slightly differing from 131 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$ computed in this study, due to the different GWP_{20} used) is 52%–67% higher than estimated with the assumptions of this paper (second and third bars). Differences are due to HJ's overestimation of the direct CO_2 emissions and the NG consumption of the blue hydrogen plant, as discussed in Section 2. According to our estimations, the SMR and ATR blue H_2 plants with high capture rates emit 81–89 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$, which represents a moderate improvement compared with direct methane combustion, as overall emissions are only 15%–23% less. With GWP_{100} (Figure 1B), the overall carbon balance somewhat improves, as emissions from blue H_2 plants reduce to around 35–40 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$, that is, 45%–51% less than direct NG combustion. However, independently of the considered GWP and of the capture rate of the blue H_2 plant, the leakage rates of this scenario are incompatible with a significant decarbonization through blue hydrogen.

Figure 1E,F refers to the scenario with a 0.2% methane leakage rate. In this scenario, the selected GWP has little influence on the overall equivalent CO_2 balance and blue hydrogen plants with high capture rate achieve emissions between 10.8 and 16.5 $g_{CO_{2\text{-eq}}}/MJ_{HHV}$, or

70%–80% less than direct NG combustion. In this scenario, residual direct emissions from the blue H_2 facility and emissions from NG processing become the main contributors.

It is also interesting to compare the resulting emissions with the limits currently discussed in the European Union for the sustainability of hydrogen production. In particular, the limit set forth by the Renewable Energy Directive (RED) for all transport renewable fuels of nonbiological origin foresees that hydrogen for the transport sector has to be produced at or below 3.38 $kg_{CO_{2\text{-eq}}}/kg_{H_2}$, referring to a 70% reduction from a fossil fuel comparator for transport of 94 $kg_{CO_{2\text{-eq}}}/MJ_{LHV}$.[30] A lower threshold is currently assumed in the EU for the classification system for sustainable activities (EU Taxonomy Regulation 2020/852), which requires that hydrogen production remains below 3 $kg_{CO_{2\text{-eq}}}/kg_{H_2}$[34] (using GWP_{100} for methane) to be compliant with a criterion of "substantial contribution to climate change mitigation." As shown in Figure 1 (values between brackets above the bars), emissions below the threshold of the EU regulation can be achieved by blue hydrogen plants with high CO_2 capture and a methane leakage rate below about 1% (Figure 1D).

It should also be highlighted that further emissions reductions with respect to the presented figures can be obtained both by boosting the CO_2 capture rate above 90%–93%[35] and by decarbonizing the power supply in NG production and transport, either through renewable power or carbon capture and storage (CCS).

Figure 2 focuses on the ATR-based blue hydrogen process. Figure 2A shows the reduction of equivalent CO_2 emission per unit of energy achievable with the ATR blue hydrogen process compared with methane combustion as a function of the methane leakage rate. Dark- and light-blue curves refer to methane GWP_{20} and GWP_{100} respectively. Solid lines refer to reference emissions of 3. 7 g_{CO_2}/MJ_{NG} from the production, processing, and transport of the NG. Dashed lines assume that these emissions are reduced by 90% through the implementation of CCS or renewable energy sources.

Figure 2A shows that with decarbonized power supply and low methane leakage, the overall emission reduction compared with direct NG combustion is close to 90%. With methane leakage rates of 0.5%, equivalent emission reduction is 68%–73% with GWP_{20} and 77%–83% with GWP_{100}.

Figure 2B shows the corresponding emissions per kg of hydrogen produced according to the same scenario. This figure highlights that the contribution of low-carbon power supply becomes significant relative to overall emissions when low methane leakage rates are ensured. It also provides indications on the maximum admissible

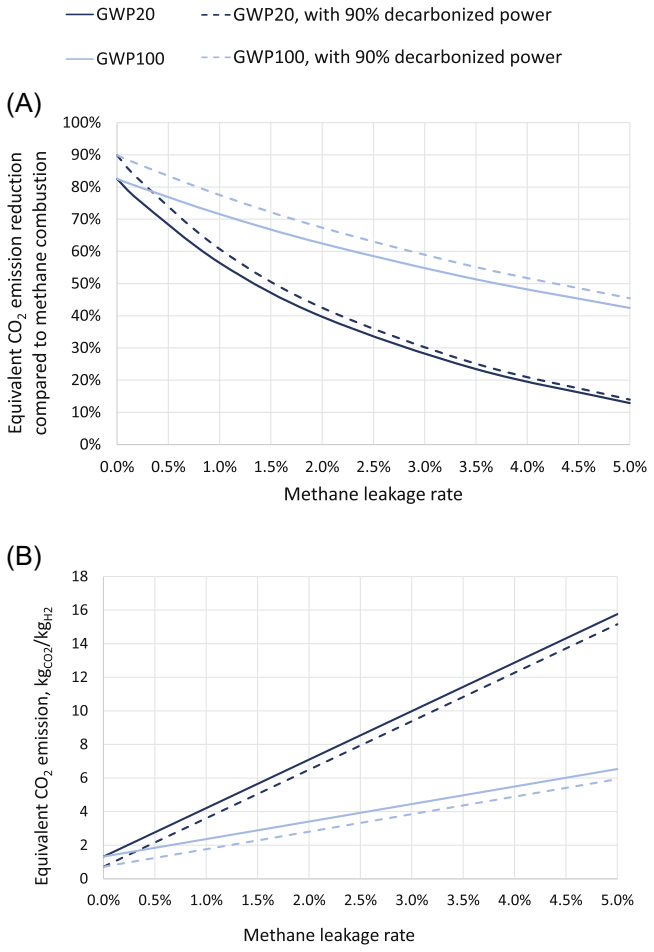

FIGURE 2 Equivalent emission reduction compared with methane combustion (A) and specific emissions per kg of H_2 (B) achievable with the ATR-based blue hydrogen plant as a function of the methane leakage rate, for different methane GWPs and different emissions from power for the natural gas supply chain. ATR, autothermal reformer; GWP, global warming potential

methane leakage rate to achieve a target emission per unit of H_2 produced. For instance, to meet the current EU taxonomy target of 3 $kg_{CO_{2\text{-eq}}}/kg_{H_2}$ (based on GWP_{100} for methane), a methane leakage between 1.5% and 2% may be admissible depending on the carbon intensity of electricity used in the NG supply chain. This result suggests that more ambitious emission targets could be set when emissions from methane leakage are tackled.

5 | CONCLUSIONS

To provide stakeholders and policymakers with reliable results on the environmental impacts of blue hydrogen, a rigorous and systematic method is required for calculating the heat and mass balances of these plants. The use of

real-world data related to a few existing SMR plants and first-of-a-kind power plant equipped with CO_2 capture is misleading, because those plants were not designed to minimize CO_2 emissions. A blue hydrogen plant built with today's technology and the aim of minimizing emissions would achieve far higher CO_2 capture rates. Moreover, the upstream leakage rates used by HJ are very high compared with both the NG value chain in many countries and emission reduction targets achievable with conventional technologies at low (even negative) costs. The analysis by HJ correctly points out that these two performance criteria are crucial in the design of blue hydrogen plants. However, the quantitative values assumed by HJ lead to implausibly high blue hydrogen emissions for decarbonizing economies. Hence, the conclusions of HJ, some of which are cited in the introduction, are based on an extremely selective and unrealistic set of assumptions and cannot be reasonably generalized for blue hydrogen production.

There are varying opinions in the scientific, industrial, and policy arena on the role of blue and green hydrogen in sustainable energy systems in the long term and during the transition phase. Assessments of blue and green hydrogen production and use in scientific papers should be rigorous, systematic, and technology-neutral, to provide unbiased data and propose metrics to guide stakeholders' decisions and support scenario analyses. In order for blue hydrogen to have a role in the transition to a decarbonized economy, we believe that its greenhouse gas emissions should be substantially lower than the direct use of NG and therefore it is necessary to:

- adopt hydrogen production processes and CO_2 capture technologies ensuring high CO_2 capture rate, preferably above 90%;
- develop a low-emission NG supply chain, minimizing methane leakage and adopting low-carbon power generation (either through CCS or renewable energies) for power supply; and
- adopt a life cycle approach based on reliable accounting of the methane leakage in the evaluation of the emissions in blue hydrogen production.

CONFLICTS OF INTEREST

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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