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Towards a Safe Hydrogen Economy: An Absolute Climate Sustainability Assessment of Hydrogen Production

Kevin Dillman [1],* and Jukka Heinonen [2]

[1] Department of Environment and Natural Resources, School of Engineering and Natural Sciences, University of Iceland, 107 Reykjavík, Iceland
[2] Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland, 107 Reykjavík, Iceland
* Correspondence: kjdillman@hi.is

Abstract: Policymakers and global energy models are increasingly looking towards hydrogen as an enabling energy carrier to decarbonize hard-to-abate sectors (projecting growth in hydrogen consumption in the magnitude of hundreds of megatons). Combining scenarios from global energy models and life cycle impacts of different hydrogen production technologies, the results of this work show that the life cycle emissions from proposed configurations of the hydrogen economy would lead to climate overshoot of at least 5.4–8.1× of the defined "safe" space for greenhouse gas emissions by 2050 and the cumulative consumption of 8–12% of the remaining carbon budget. This work suggests a need for a science-based definition of "clean" hydrogen, agnostic of technology and compatible with a "safe" development of the hydrogen economy. Such a definition would deem blue hydrogen environmentally unviable by 2025–2035. The prolific use of green hydrogen is also problematic however, due to the requirement of a significant amount of renewable energy, and the associated embedded energy, land, and material impacts. These results suggest that demand-side solutions should be further considered, as the large-scale transition to hydrogen, which represents a "clean" energy shift, may still not be sufficient to lead humanity into a "safe" space.

Keywords: hydrogen economy; absolute sustainability; safe operating space; hydrogen policy; hydrogen certification

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1. Introduction

Hydrogen is increasingly seen as a means to combat climate change due to its oft-cited ability to 'decarbonize difficult to abate' sectors. These sectors include heavy-duty transport, shipping, chemicals production, and industry (where high temperatures are needed), which see challenges in traditional decarbonization pathways such as direct electrification or increased energy efficiency sufficient to achieve stated climate goals [1]. Hydrogen can help overcome these challenges, acting an enabling technology for the energy transition because of its ability to primarily do three things as an energy carrier [2,3]:

1. Act as storage for surplus intermittent renewable electricity sources
2. Assist in decarbonizing hard-to-electrify sectors (i.e., long-distance transport and heavy industry)
3. Serve as a feedstock in chemical and fuel production (potentially replacing fossil fuels, dependent on use case).

Interest in hydrogen is unquestionably growing rapidly. While hydrogen has had other stop-and-start moments since the publication of *The Hydrogen Economy* [4], never has it seen the level of political and financial commitments put forth in recent years. In 2017, only Japan had a hydrogen strategy in place. By September 2022, over 26 countries had established hydrogen strategies [5], with more having announced their development [6]. This acknowledgement of hydrogen's growing role in the future of the energy economy can be seen further in global energy scenarios that historically have overlooked or been uncertain of hydrogen's role [7]. However, such models have recently had a more consistent inclusion of hydrogen [8], such as those developed by the International Energy Agency (IEA) [5,9], the Hydrogen Council [10,11] and the Energy Transitions Commissions [12,13]. Across these models, hydrogen is predicted to meet a range between 7–24% of final energy demand by 2050, with an estimated hydrogen demand of 500–800 Mt. Though these ranges still represent a large margin of uncertainty regarding the energy carrier's proliferation, the scale of the inclusion of hydrogen use across these models illustrate the expectations of hydrogen's growing global importance. Additionally, the scenarios that take the most aggressive decarbonization approaches have been found to see higher rates of hydrogen use, suggesting its role as an enabling technology for the energy transition [7].

Interest in hydrogen can further be attributed to the changing geopolitics of energy associated with the transition and energy security [8]. The Russia-Ukraine crisis put these issues at the forefront of the rapidly changing geopolitical reality, especially for the European Union (EU) [14]. This can be seen in the European Commission's REPowerEU plan, put together to rapidly reduce reliance on Russian gas, where the production and use of green hydrogen and the acceleration of the hydrogen economy sees a notable focus [15].

While hydrogen has been used in energy models to achieve net zero pathways, results from recent life cycle assessment (LCA) studies on different means of hydrogen production bring cause for concern when discussing the scale of demand being suggested in these global energy models (i.e., [16,17]). To understand why, it is important to recognize that hydrogen is an energy carrier, where an energy carrier acts as an intermediary between primary energy sources and the final user [3]. Thus, the greenhouse gas (GHG) emissions associated with producing hydrogen are largely determined by the means by which the hydrogen is produced. As an energy carrier, hydrogen is a commodity, and one which can be produced in a myriad of ways, as it does not exist naturally in nature [18].

The production of hydrogen is often described using a colour scheme where black (gasification) and grey hydrogen (steam methane reforming [SMR]) represent production during the processing of fossil fuels (coal and natural gas respectively). These processes lead to significant GHG emissions both from CO_2 process emissions as well as fugitive methane emissions both upstream and downstream (where IRENA [6] estimates emissions of 9–11 $kgCO_2eq./kg$ hydrogen for SMR and 18–20 for Gasification). Currently, 96% percent of hydrogen is produced through these means [19]. Blue hydrogen represents the "clean" version of black and grey hydrogen in which grey and black hydrogen production pathways are paired with carbon capture and storage (CCS) to reduce emissions. However, recent studies have shown the risk of blue hydrogen, where fugitive emissions and differing capture rates of CO_2 in the CCS system could lead to an emission reduction of only ~10–66% from grey hydrogen dependent on operating conditions [17,20]. While experts have begun to recognize the long-term limitations of blue hydrogen in terms of alignment with net-zero futures, they are still highly present in global energy models and the near-to-mid-term expectations of hydrogen economy development [5,21,22]. Thus, it is an important production method that needs to be considered in this work. Green hydrogen is hydrogen produced through electrolysis using renewables such as solar, wind, or hydropower. Electrolysis requires significant energy inputs, however, and the capacity of electricity required to meet large-scale electrolysis demand has been questioned [23]. Electrolysers can also be paired with nuclear (pink hydrogen) or the grid (yellow hydrogen) [24], though these have their own pitfalls and debates, such as the public's scepticism of nuclear energy [25], and the existence of few electrical grids where yellow hydrogen would be environmentally viable [24]. Lastly, turquoise hydrogen describes hydrogen production through methane pyrolysis, where natural gas is decomposed at high temperatures into solid carbon and hydrogen, though turquoise hydrogen production is rarely if at all included in any hydrogen models due to its nascency [24]. Global energy models are increasingly incorporating hydrogen into their net zero pathways, yet there is a notable lack of transparency behind the assumptions in terms of both technology (i.e., the type of hydrogen being produced in the models) as well as the associated environmental impacts associated with the means of hydrogen production [7,26]. This lack of transparency and clarity on environmental impacts extends to national hydrogen strategies [27]. In almost every model, however, generally, only the existing fossil fuel-based production (grey and black), blue, and green hydrogen (where these represent the 'clean' hydrogen options) are considered.

The goal of these energy models is to identify pathways which can ensure our ability to remain within a 'safe' operation space, where this space describes the ability of society to maintain Earth Systems such that they do not surpass the planetary boundaries and lead to non-linear changes which could potentially impact social development [28,29]. Climate change represents one of these planetary boundaries, and the Intergovernmental Panel on Climate Change (IPCC) has estimated that from the beginning of 2020, to have a 67% probability of ensuring warming below 1.5 °C (considered to be the 'safe' space for global warming), the Earth's atmosphere has an approximate carbon budget of 400 $GtCO_2$ remaining [30]. With the Carbon Budget Project's estimate of 42.2 ± 3.3 $GtCO_2$ and 37.4 ± 2.9 $GtCO_2$ global carbon balance for the years 2020 and 2021, respectively [31,32], this suggests that from 2022 onward we have roughly 320 $GtCO_2$ left (with relative uncertainty both on the emissions and the warming potential). The IPCC's Working Group II Report for the Sixth Assessment Report highlighted the importance of staying below 1.5 °C, where if we surpass these levels, our ability to adapt to climate change rapidly lessens [33].

With the remaining global carbon budget in mind (~320 $GtCO_2$eq.), considering that by 2050, across major global energy models, annual hydrogen use is estimated to be between approximately 530–813 megatons, contradictions arise. With the suggested emission factor for hydrogen to be certified as low-carbon at 3 and 4.37 $kgCO_2$eq. per kg H_2 (36.4 MJ per kg H2 using the LHV of hydrogen, estimated by CertiHy [34] to be a 60% of the emissions from SMR, the leading product method of H2) according to the EU Taxonomy [35] and CertiHy [34], respectively, the annual emissions from hydrogen would be on the scale of gigatons in 2050. This estimate only considers the use of low-carbon hydrogen, and currently, most of the hydrogen produced falls into more GHG-intensive colour categories. While these EU Taxonomy and CertiHy benchmarks are, of course, likely to reduce in the future, the magnitude of change in required emissions per unit hydrogen that would be required to achieve this 'safe' space for the hydrogen economy in terms of climate change impacts is thus far unclear. Further, the setting of the threshold values to be considered low-carbon are political processes potentially subject to lobbying, which could slow progressive reductions in them.

Synthesizing, energy models are increasingly dependent on hydrogen (though to different extents) to achieve net zero pathways, yet LCA studies have shown that producing hydrogen of any colour is not without consequence. If the goal of the hydrogen transition is to ensure that society can achieve a net zero global economy by 2050, it should be ensured that this is indeed the reality. Energy models have incorporated hydrogen at scale to reduce emissions but lack transparency. Hydrogen LCA studies typically consider hydrogen at the scale of a functional unit (i.e., one kg of H_2). The IPCC AR6 does review hydrogen LCA results and scenarios, but the results are scattered and vague in terms of how specific hydrogen pathways/scenarios may align with 1.5 °C goals [36]. Lastly, "low-carbon" certification program benchmarks are understandably set at too high of a level currently, but how they will scale downwards remains ambiguous [37].

Lacking in the literature, therefore, is the bridging of these two fields of study to ensure that the expansion of the hydrogen economy can act as a transition enabler to aid in leading humanity into a 'safe' operating space, which society has been rapidly exiting [38].

To avoid the worst climate impacts, the IPCC has suggested that rapid decarbonization is needed, with much of this decarbonization needing to occur by 2030, to stay in this safe space [33]. This work, therefore, poses the research question of assessing the role of hydrogen in keeping humanity in a net zero 'safe' operating by 2050. This question will be answered by performing an absolute climate sustainability assessment (ACSA), through a bridged assessment of global energy models and hydrogen LCA studies [39]. This life cycle perspective has been called for in the literature, as the emission accounting boundaries in national hydrogen strategies have been largely inconsistent and these have significant emission implications [27,37]. Thus, answering this question is imperative for intergenerational sustainable development. If the mitigation potential of the hydrogen economy is misrepresented and/or is implemented for self-serving purposes such as geo-political advantage [40] or protection of specific sectors, such as oil and gas [41], the colossal financial and infrastructure investments required to implement a global hydrogen economy presents the risk of entering a path dependent lock-in which does not do enough to keep us in a 'safe' operating space. This fear is accompanied by concerns that the hydrogen economy would represent a misallocation of priorities away from energy efficiency and direct electrification with renewables [2]. Second, this work additionally attempts to provide a first illustration of how low-carbon hydrogen certificate emission factor qualifications should regress to support low-carbon hydrogen economy development. This helps illustrate when current production methods may no longer qualify as low-carbon and can be used for guidance by certification programs to consider how they should downscale their benchmarks moving forward.

To answer the question of if the life cycle impacts from the hydrogen economy in global energy models would lead society in a 'safe', net zero aligned space, first, the ACSA methodology is shortly described. Then the global energy models and initiatives which incorporate hydrogen are described. Scenarios from these models were then considered, recognizing their varying, yet comparable, levels of demand, technological splits (green or blue), and estimates of hydrogen's role in final energy demand. Life cycle emissions factors from the literature were then used to estimate the cumulative and annual life cycle GHG emissions until 2050 from the hydrogen economy. These estimates were then compared to estimated rates of carbon sequestration by 2050 along with the remaining carbon budget to assess the alignment of projected hydrogen economy proliferation in the different scenarios with the goal of entering a 'safe' space compatible with below 1.5 °C development. These results were then related to existing hydrogen certification schemes to map a pathway for a 'safe' hydrogen economy. This aimed to provide a first illustration of how low-carbon hydrogen certificate emission factor qualifications should regress to support low-carbon hydrogen economy development. This helps illustrate when current production methods may no longer qualify as low-carbon and can be used for guidance by certification programs to consider how they should downscale their benchmarks moving forward.

This work provides an absolute climate sustainability assessment for the nascent hydrogen economy, providing academic value to these fields of research, where it highlights the importance for energy models to provide both technological and environmental transparency, in terms of the means of production for hydrogen and the emission factors of these means [7]. Further, it moves the conversation beyond the relative sustainability improvements of the hydrogen economy into an absolute context, with the need for such assessments increasingly called for in the literature [39,42,43]. For policymakers and the hydrogen community, this work highlights the need to tie emission factors and certification standards to scientific thresholds for a safe space. This supports the identified lost environmental rigor of the characterizing 'low-carbon' hydrogen in national hydrogen strategies [27].

While this approach taken in this work is simplistic, it is useful in understanding the limitations of the currently proposed hydrogen economy configurations in global energy models and can help interpret what changes need to be made if it were to be a successful energy vector for economy-wide deep decarbonization. This article does not position the hydrogen economy as the sole decarbonization pathway or compare it to other pathways, nor does it seek to give an opinion on whether it should be developed or not (because it may well be needed to achieve deep decarbonization). Instead, it seeks to provide a simple estimate of the GHG emissions associated with the various proposed configurations of global energy models to interpret the impact of various scales and illustrate the potential challenges of the hydrogen economy as an energy vector. This can help clarify what potential adaptations could be needed to achieve deep decarbonization.

2. Materials and Methods

Using some of the global models which incorporate hydrogen in their assessments, such as the IEA [9], the Hydrogen Council [10,11,44], and the Energy Transitions Commissions [12,13], the ACSA approach taken in this work took an LCA perspective to provide a range of potential outcomes of different scenarios across the models. First, this ACSA methodology is shortly described with the scope of the assessment described. Next, key variables from these scenarios (and derived scenarios) were extracted from the cited global energy models. LCA data for each hydrogen type (i.e., grey, blue, green, etc.) was then extracted from the literature. These values were used to perform the assessment and derive the results.

LCAs typically consider the relative environmental impacts (of different impact categories such as climate change or eutrophication) of two alternative products [45]. While these relative impacts can assist in providing the information needed to increase the environmental efficiency of different products or services, the exponential growth of socio-economic trends and total human consumption has outpaced improvements in environmental efficiency. This has led to similar exponential changes to Earth systems, threatening ecological breakdown and the approach towards ecological tipping points [38,46]. absolute sustainability approaches, and specifically LCA-based absolute sustainability assessment, have thus been developed to connect products, sectors, and industries to the finite carrying capacity of Earth [39,43]. Within this approach, clear identification of the following has been considered to be valuable in clearly defining the scope of the absolute assessment [39]: the anthropogenic system under consideration, the earth system state/carrying capacity (i.e., for climate change, the concentration of carbon in the atmosphere and the remaining carbon budget), and how the carry capacity is shared for the system and allocated.

Therefore, disclosing these aspects, first, the anthropogenic system under consideration is the hydrogen economy, from cradle-to-gate, with the gate being the location of production. Hydrogen transport infrastructure was considered to be relevant but was not included in the scope due to lacking available and consistent data in the literature, particularly regarding distance and means of transport (i.e., liquefaction versus transformation) [6]. Further, this work only considered supply-side configuration and not demand-side configuration (i.e., only how the hydrogen would be produced and not how it would be used).

The Earth system state considered in this assessment was the concentration of GHGs in the atmosphere and the carrying capacity was determined to be the remaining carbon budget to remain below 1.5 °C warming (estimated in this work to be 320 $GtCO_2$. as described in Section 1). The carrying capacity in terms of carbon budget was not allocated due to the potential scale of GHG emissions from the hydrogen economy. As a further analysis, with the IPCC's declared necessary target of achieving a net zero global economy by 2050 [47], to provide an estimate of the 'safe' operating space for the hydrogen economy in 2050, the total 'safe' space was determined as the IEA's Net Zero Emission scenario estimated combined 2050 direct air capture and carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS) [9]. This was then allocated such that the 'safe' space in each scenario would equal the total capture times the product of the proportion of global emissions caused by energy system (currently estimated to be 73% [48] and the percent of CED met by the hydrogen economy in the associated scenario.

Table 1 describes the assessed scenarios from the global energy models discussed, including by 2050, the estimated total hydrogen demand, the blue/green hydrogen split, and the percent cumulative energy demand met by hydrogen. As noted by [7], the data availability of these models is low, requiring assumptions to be made in terms of hydrogen demand growth rates, technological integration, and blue/green hydrogen splits rates. The IEA scenarios had greater detailed data (provided in 5-year intervals), however, the

Hydrogen Council and Energy Transitions Commissions only provided estimates for 2030 and 2050. Due to the lack of data across models, annual demand estimates across these time periods for these models were assumed to be linearly increasing. All models assumed only the use of green or blue hydrogen in terms of low-carbon solutions, with different splits estimated in the different models, though the Hydrogen Council left their split between blue and green ambiguous dependent on cost developments for each production technology. Therefore, three scenarios of different blue/green splits were presented for the Hydrogen Council to consider the implications of these development pathways. The Energy Transitions Commission phased out grey and brown hydrogen by 2035 [35], the Hydrogen Council by 2040 [11], while the IEA continued their use until 2050 [9]. This transition rate is an additional driver of emissions, where the high use of grey and brown hydrogen early in the hydrogen economy's development will lead to greater emissions.

Table 1. Overview of scenarios from global energy models incorporating hydrogen. Table includes the resulting cumulative emissions from annual demand of hydrogen and associated GHG emissions according to the estimated technological production split.

Model	Scenario Name	Scenario Code	% of Global Energy Demand Met by Hydrogen by 2050	Total Hydrogen Demand in 2050 (in Mt)	Hydrogen Use by Colour by 2050 (Green/ Blue Hydrogen Split)
International Energy Agency	Sustainable development scenario	IEA SDS	8.8%	287.2	59/40
	Net Zero Emission scenario	IEA NZE	20.3%	528.2	59/40
Hydrogen Council	High green	HC G	18%	650	75/25
	Even split	HC 50/50	18%	650	50/50
	High blue	HC B	18%	650	25/75
Energy Transitions Commission	Low demand	ETC LD	13%	540	85/15
	High demand	ETC HD	24%	813	85/15

Table 2 shows the life cycle emissions from the different means of hydrogen production. The wide ranges illustrate the degree of uncertainty and potential outcomes for each production pathway. This was particularly pronounced for green and blue hydrogen, due to the nascency of the production technologies. It was assumed all electricity would be produced either by wind or solar, and it would be an average 50/50 split between the two renewable energy technologies. Further, how the life cycle emissions would be reduced over time was estimated using the literature, and when temporal estimates were not available, the lowest emission estimate was considered the average by 2050.

Table 2. Assumed life cycle emissions (in $kgCO_2eq./kgH_2$ in GWP100) for hydrogen produced by different means.

Means of Production	High	Low	Expected 2020	Expected 2050	Source
Coal Gasification	25.31	14.40	19.14	19.14	[16]
SMR	15.86	10.72	12.4	12.4	
Green—wind	2.20	0.80	1.34	0.80	
Green—solar	7.10	1.99	3.74	2.99	
Green—assumed 50/50 split	4.65	1.40	2.54	1.90	Calculated
Blue	12.70	2.70	8.04 [a]	2.70 [b]	[20]

[a]: Emission factor at 1.54% fugitive emissions and 85% capture from [17], with an average fugitive emissions performance and high carbon capture.; [b]: Estimated emission factor at 1.5% fugitive emissions and 93% capture rate [20], which represented the lowest estimated blue hydrogen emission factor available in the literature.

As discussed, blue hydrogen describes the production of hydrogen following the SMR process with the exception that the carbon dioxide produced during this process would be captured. There still exist fugitive methane emissions that occur both upstream and downstream, however [49,50]. The capture rate of carbon dioxide in this process and the up and downstream fugitive emissions are the most impactful variables determining the life cycle emissions of blue hydrogen production [20]. This work used the life cycle emissions associated with blue hydrogen production with 2.54% fugitive emissions and 85% carbon capture [17]. To date, 90% carbon capture has been the highest capture rate seen at SMR carbon capture plants, with ranges from 53–90% [51], higher rates of capture are feasible, but they have yet to be proven at scale [14]. Additionally, in a study on fugitive methane emissions in shale gas production, the volume-weighted average was estimated to be 2.6% [52], and this is not taking into account downstream emissions from storage and transport of the methane, which potentially could account for another 0.8% of methane emissions [17]. Thus, this expected estimate is a somewhat favourable estimate for fugitive emissions from blue hydrogen. It is then estimated that blue hydrogen on average would go down to 1.5% fugitive emissions and 93% capture as the average life cycle emissions for blue hydrogen [20]. All other ranges were extracted from [16]. SMR and Gasification do not show improvement rates because the technological improvements of these production types are the application of CCS, redefining the projects as blue hydrogen.

3. Results

The key findings of this work showed that the life cycle emissions from current proposed configurations of the hydrogen economy in scenarios from global energy models would lead to climate overshoot of 5.4–8.1× by 2050, where climate overshoot was defined in this work as the emissions in that year as the ratio of the estimated 'safe' space in that year. The cumulative consumption of 8–12% of the remaining carbon budget. This work suggests that a ratcheting mechanism is needed for defining a science-based definition for 'clean' hydrogen (<0.27–0.44 $kgCO_2eq/kg\ H_2$), agnostic of production technology, that would be compatible with a 'safe' net zero aligned development of the hydrogen economy. Collating the results of the most prominent blue hydrogen LCA studies, such a ratcheting mechanism would deem blue hydrogen economy environmentally unviable even under ideal operating conditions (<0.2% fugitive emission rate and >93% CC rate) by 2025–2035. However, the prolific use of green hydrogen is also problematic because of the electrical efficiency of electrolysers (currently ~50 kWh per kg H_2) which would require significant use of renewable sources, and associated embedded energy, land, and material impacts. These results suggest that demand-side solutions need to be further considered, as the large-scale shift to hydrogen may still not be sufficient in leading humanity into a below 1.5 °C 'safe' operating space.

The following subsections describe how these results were derived. First, the annual emissions from the hydrogen economy are illustrated temporally, with an example of the composition of the emissions provided. A cumulative emission perspective is then compared to the remaining 1.5 °C carbon budget to assess the hydrogen economy's consumption of this budget. Using the annual emissions by 2050, the 'safe' space and the overshoot of it in each scenario for the hydrogen economy were then assessed. Lastly, some of the additional 'safe' implications of green and blue hydrogen are discussed, surrounding the certifications and what a 'safe' definition would be for low-carbon hydrogen. The following section discusses the implications of these results and concludes.

3.1. Annual Emissions

As highlighted in Table 1, Hydrogen demand is expected to grow through 2050 in all models, and this section illustrates the impacts of this significant increase in demand. According to the demand and life cycle emissions found in Tables 1 and 2, the annual emissions from hydrogen production in each of the seven included scenarios can be seen in Figure 1a, with Figure 1b showing an example breakdown per hydrogen type of the IEA

NZE scenario. By 2050, in Figure 1a the HC B scenario led the highest annual emissions, followed by the ETC HD demand scenario. This highlights both the importance of high demand as well as the impacts of leaning too heavily on blue hydrogen. Figure 1b illustrates an example of the contribution of each production technology over time, where even though the IEA NZE scenario sees a 60/40 split of green hydrogen to blue hydrogen, blue hydrogen accounts for disproportionately more emissions. Further, it can be seen that almost all of the scenarios are either close to or above the red line in Figure 1a, where this line represents the IEA's estimations of total carbon capture of 1.56 Gt CO_2 sequestered by 2050 [9]. This highlights how at this rate, the hydrogen economy itself would lead to more emissions than planned CCS, which challenges the potential of achieving net zero emissions by 2050.

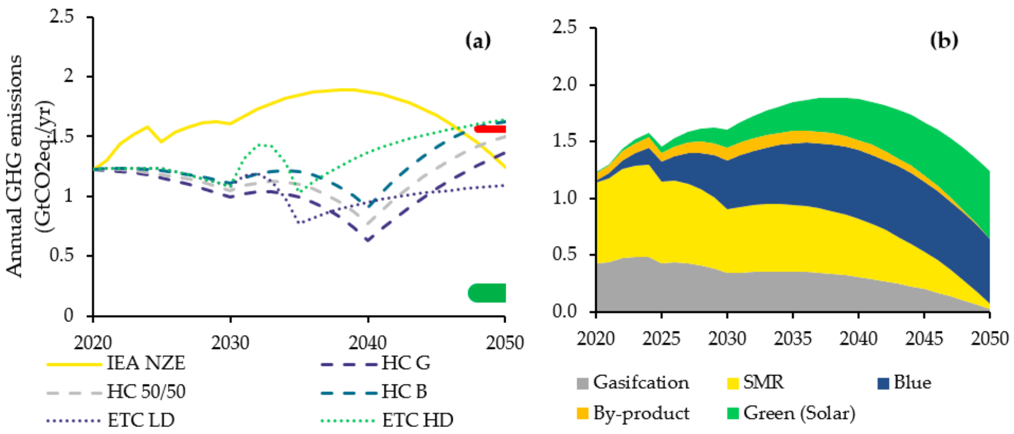

Figure 1. (**a**) Annual GHG emissions from hydrogen demand by model and scenario. The red line extending from 2050 represents the IEA's estimations for cumulative carbon capture in 2050. (**b**) Annual GHG emissions from hydrogen demand from the IEA NZE scenario (this scenario was used because it was the scenario with the greatest available data with the least use of assumptions) disaggregated by hydrogen production type as an example of the internal composition of the emission from each production type. It can be seen that the total of (**b**) aligns with the curve shown in (**a**) for the IEA NZE scenario (by-product hydrogen was assumed to have the same emission factor as gray hydrogen).

3.2. "Safe" Space Implications

Table 3 below considers the 2050 implications of these scenarios, where the cumulative and estimated annual emissions in 2050 associated with hydrogen demand are shown per scenario, where the high and low ranges for emissions associated are provided to consider the uncertainty associated with estimating the life cycle emissions for each hydrogen production type over time. First, using the estimates provided by following the allocation procedure of all carbon capture in 2050 described in the methodology section, the potential overshoot of emissions from hydrogen demand for each scenario was estimated, and an overshoot between ~6–8× across scenarios was seen, with the most pessimistic scenarios seeing overshoot >20×. To estimate what the life cycle emissions of hydrogen would need to reach to stay within an estimated "safe" space by 2050 to allow for net zero emissions, it was estimated that the average life cycle emissions for all hydrogen consumed should be approximately between 0.27–0.44 $kgCO_2eq/kg\ H_2$, with this estimate dependent on total hydrogen demand and percent of final CED met by hydrogen. These results contrast sharply with the E.U. Taxonomy's and CertiHy's respective suggestions for a "green certification" life cycle emissions of 3 and 4.36 $kgCO_2eq/kg\ H_2$, by a magnitude of approximately 10 to 20. It's worth noting that even in the scenarios, which used the lowest emission factor estimates throughout the entire period, a significant portion of the carbon budget is still consumed.

Table 3. 2050 implications of the hydrogen economy per model and scenario.

Model	Scenario	Total Cumulative Emissions 2020–2050 (Gt CO_2eq.)	% of Remaining Carbon Budget Consumed (2020–2050)	Annual Emission by 2050 (GtCO_2eq./yr)	2050 Safe Space for Hydrogen (GtCO_2eq./yr)	Overshoot in 2050	Necessary Average Emission Factor (kgCO_2eq./kg H_2)
IEA	SDS	25.1 (18.9–46.2)	8% (6–14%)	0.67 (0.58–2.30)	0.10	6.7 (5.8–23.0)	0.35
	NZE	50.7 (37.8–95.5)	16% (12–30%)	1.24 (1.07–4.23)	0.23	5.4 (4.6–18.4)	0.44
HC	HC G	32.4 (24.4–63.8)	10% (8–20%)	1.37 (1.12–4.33)	0.20	6.8 (5.6–21.7)	0.32
	HC 50/50	35.4 (26.5–76.6)	11% (8–24%)	1.50 (5.64–1.33)	0.20	7.5 (6.7–28.2)	0.32
	HC B	38.4 (28.6–89.5)	12% (9–28%)	1.63 (6.95–1.54)	0.20	8.1 (7.7–34.7)	0.32
ETC	ETC LD	33.2 (24.4–66.2)	10% (8–21%)	1.09 (0.86–3.16)	0.15	7.3 (5.7–21.1)	0.27
	ETC HD	41.2 (29.9–86.8)	13% (9–27%)	1.64 (1.30–4.76)	0.27	6.1 (4.8–17.6)	0.34

3.3. Additional "Safe" Considerations for Green Hydrogen

While Figure 1b illustrated the disproportionate impact of blue hydrogen, green hydrogen is not without its faults. Table 4 illustrates one of the most notable challenges with green hydrogen, which is the vast amount of electricity which would be required to produce the modelled amount of green hydrogen [5]. Electrolysis is an electricity intense process, where [16] considered a polymer electrolyte membrane (PEM) electrolyser with a production efficiency of 51 kWh/kg H_2, and [53] estimated that using the IEA's [22] future estimates of the still underdeveloped solid oxide electrolyser cell (SOEC) electrolyser technology, that by 2040 the efficiency will be ~35 kWh/kg H_2. Using this future estimate to take technological development into account, the electricity needed for electrolysis according to green hydrogen demand (as a proportion of total hydrogen demand) was estimated per scenario. This was then compared to the most recent number for total energy supplied by renewable sources [54]. It was found that by 2050, just for electrolysis, green hydrogen would require between 0.9 and 3.7 times the amount of all renewably generated electricity today (with the most recent data from 2019 and where hydropower accounted for 66% of the renewable electricity generated). Further, the total land required for the capacity of solar and wind to produce this 2050 electricity was estimated. Land use for solar and wind was estimated to range from 2–10 and 0.5–2 W_e/m^2 [55], respectively, providing the range estimates. The average global capacity factors for solar and wind were estimated to be 20% [55] and 28.5% [56] and it was estimated 64% of wind potential exists terrestrially with the remaining 36% to be offshore wind potential. The results show that the global requisite solar land footprint would be in the range of 0.3–6.9 million square kilometres and for wind a terrestrial land footprint of 0.7–12.4 million square kilometres. For wind, on the low end of the spectrum, this would equal roughly the total land area of the country of Chile, and for wind on the furthest estimate, the terrestrial footprint would represent approximately 9.5% of the global land area. It is worth noting that, of course, technological and efficiency improvements of renewables and electrolysers will serve to reduce these numbers, but these broad estimates serve the purpose of highlighting the scale of electricity that would be required to power the assumed hydrogen economy configurations across the global energy models.

All of this would need to be achieved on top of simultaneously decarbonizing electrical grids, requiring significantly further capacity of wind and solar, and where grids are likely to see increased electricity demand from other parts of the economy as electrification rates for transport and heating increase [5,54]. While hydrogen can be used to seasonally balance loads of RE in the electrical grid, this is only expected to be a small portion of hydrogen production, for example where the ETC expects this to account for 10% and 16% in the ETC HD and ETC LD scenarios respectively [13]. These estimates further do not consider the implications of the land use (i.e., emissions from land use change) nor other drawbacks associated with the mass use of renewables, such as high material use, especially of rare materials [57], and low energy return on energy invested (EROEI) [58].

Table 4. Electricity demand and associated land footprints from green hydrogen demand per model-scenario.

Model	Scenario	Electricity Demand per Scenario at 2050 (GWh)	Multiplier of Todays Annual RE Generation (2019)	100% Solar Land Footprint Range (in m km^2)	100% Wind Terrestial Footprint Range (in Million km^2)	100% Wind Offshore Area Required Range (in Million km^2)
IEA	SDS	5,926,550	0.91	0.34–1.69	0.76–3.04	0.43–1.71
	NZE	10,907,330	1.67	0.62–3.11	1.4–5.59	0.79–3.15
Hydrogen Council	High green	17,062,500	2.61	0.97–4.87	2.19–8.75	1.23–4.92
	Even split	11,375,000	1.74	0.65–3.25	1.46–5.83	0.82–3.28
	High blue	5,687,500	0.87	0.32–1.62	0.73–2.92	0.41–1.64
Energy Transition Commission	Low demand	16,065,000	2.46	0.92–4.58	2.06–8.24	1.16–4.63
	High demand	24,186,750	3.70	1.38–6.9	3.1–12.4	1.74–6.98

3.4. Additional "Safe" Considerations for Blue Hydrogen

The ETC scenario highlighted the reduced role blue hydrogen would need to ensure net zero development of the hydrogen economy, which led to their assumed 85 G/15 B split. Figure 2 illustrates why many have now positioned blue hydrogen as a transition technology, suitable only for near-and-mid-term hydrogen development. The potential life cycle emissions for blue hydrogen were estimated through a multi-independent variable linear regression at different carbon capture and fugitive emission rates. The Figure shows that only at the highest rates of carbon capture and the lowest rates of fugitive emissions will the blue hydrogen produced be considered net zero aligned ('safe'). While higher rates of capture are feasible, they have yet to be proven at scale [20]. Only under ideal operating conditions could blue hydrogen be a 'safe' development at the high levels of hydrogen demand in all scenarios.

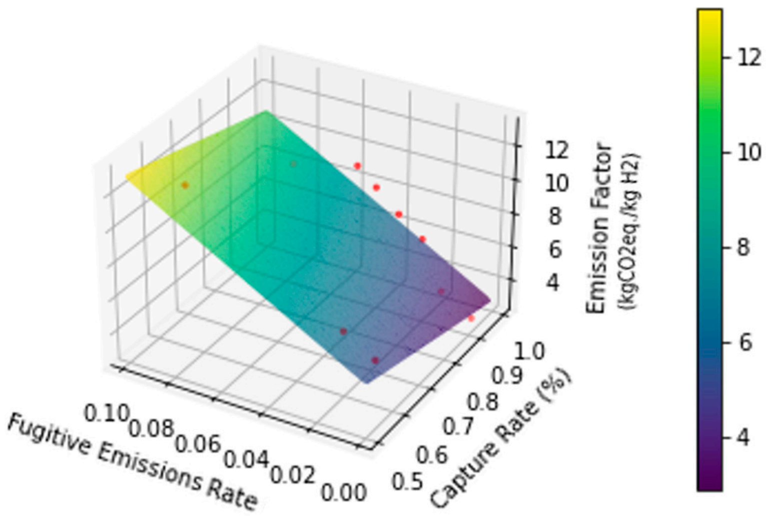

Figure 2. Linear regression (represented as the surface) of the life cycle emissions of blue hydrogen according to fugitive emission and capture rates, using data from [17,20] where actual data points are represented by the red dots. By this assessment, only operational combinations of approximately >95% capture and <1% fugitive emissions would lead below even current EU Taxonomy guidelines. Only by having near zero fugitive emissions and near perfect capture would blue hydrogen thus exist in a "safe" space for net zero development.

Extending this discussion, it is worth mentioning that the IPCC and all net zero pathways require the rapid decarbonization of the global economy in the coming decades (2020–2040). One particular area of concern when discussing blue hydrogen is that much of its global warming potential comes from methane emissions, which is a particularly potent

GHG in the shorter term, which has been identified as critical in mitigating the effects of climate change [59], if one were to consider the GWP20 (which represents the Global Warming Potential over a 20-year time span as opposed to the GWP100 typically used), the impact of blue hydrogen significantly worsens. This discussion of increased GWP20 emissions is had in both prominent blue hydrogen LCA studies available [17,20].

Further, blue hydrogen comes with a caveat. Currently, almost all Carbon Capture Utilization and Storage (CCUS) capacity globally is found at fossil fuel extraction sites [60]—Which represents the operating conditions of blue hydrogen—And this is no coincidence. The oil and gas industry is using CCUS more for utilization than for storage, where more than 75% of all currently operational CCUS projects globally are currently for the purpose of enhanced oil recovery (EOR) [61]. EOR is a process in which the captured carbon is injected into depleted oil reservoirs, which allows for the extraction of residual oil. This process thus increases fossil fuel extraction, and the retention rate of the carbon injected is highly dependent on operating and geological conditions, varying from 99% to as low as 28% [62]. In the review of LCA impacts of enhanced oil recovery, Sekera and Lichtenberger [60] found that enhanced oil recovery has a net-positive emission outcome. Additionally, this enhanced oil recovery means greater extraction of fossil fuels, and it has already been shown that if humanity wants to stay within 1.5 °C, we need to leave carbon in the ground, not extract more [63]. Thus, blue hydrogen has the potential to lock-in the ever-greater extraction of oil and gas, and any gains made by low-carbon hydrogen could likely be more than offset and could lead humanity down a very dangerous path of warming.

3.5. Science-Based "Clean" Certification for Hydrogen

With the 'safe' space and life cycle emission factor (agnostic of production technology) for the hydrogen economy estimated to be ~0.27–0.44 by 2050 (See Table 3), the question then becomes how can these results be used for the 'safe' governance of the hydrogen economy? As discussed, green definition and global certification systems from the likes of CertiHy and the EU Taxonomy have suggested between 3 and 4.37 $kgCO_2eq/kg\ H_2$, respectively. While this currently is sufficient at lower levels of hydrogen demand and the lead time for decarbonization, it becomes clear however that this will not always be the case as hydrogen demand and the need to rapidly decarbonize increase in tandem. Thus, Figure 3 imagines what a 'safe' ratcheting mechanism for these green definitions and certifications would look like and what the implications are for the different expected levels of different means of producing said hydrogen, following a similar mindset as the Science-based target initiative [64]. Modelling this linearly from the current number to 2050, it can be seen that both blue hydrogen with fugitive emissions at 1.5% and carbon capture rates of 93% and green hydrogen produced with solar could be currently considered 'unsafe' or can be expected to be by 2025 if such a linear mechanism was used. Blue hydrogen with significantly low levels of fugitive methane emissions (0.2%) and high capture rates (93%) would then become 'unsafe' between approximately 2025–2033. Green hydrogen, estimated as a 50–50 split between electrolysis powered by wind and solar is similarly estimated to become 'unsafe' between 2025–2038. Electrolysis powered 100% by wind power was considered to be the only form of hydrogen production that would be aligned with achieving net zero by 2050 in terms of life cycle emissions. The life cycle emissions associated with solar to produce green hydrogen thus will need to decrease more rapidly in order to remain in a 'safe' space for green hydrogen production.

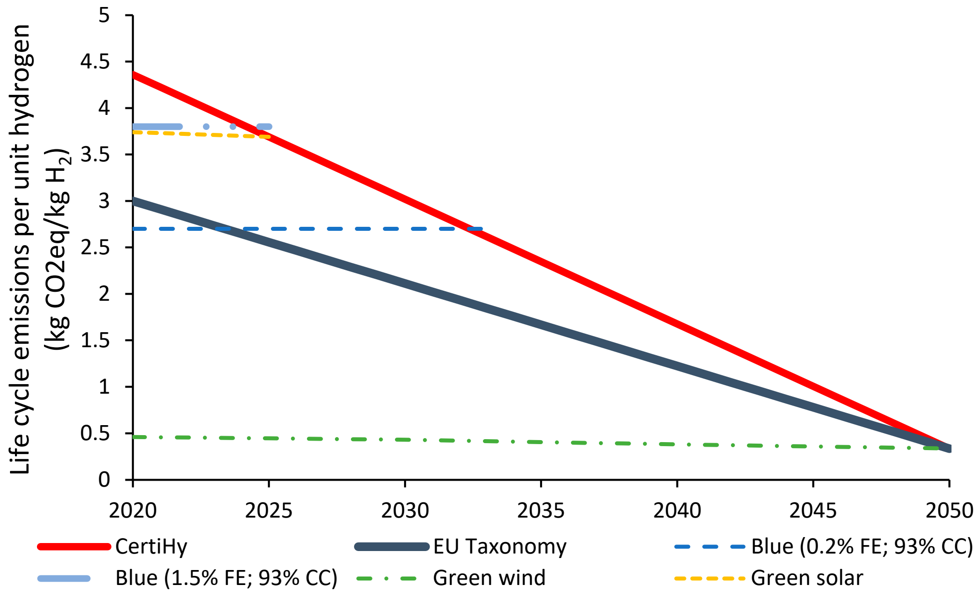

Figure 3. A mapping of an estimation of the "safe" space hydrogen life cycle emissions, with the GO level for net zero friendly hydrogen depicting a linear decrease from the current suggested level for "environmentally safe" hydrogen to the estimated levels depicted in Table 2. The other lines illustrate the life cycle emissions from different means of production for blue and green hydrogen.

4. Discussion

The results of this work make clear that the scale of hydrogen production prospected by global energy models may challenge society's ability to reach the 'safe' space of achieving net zero GHG emissions by 2050. Broken down to its most simple components, this is because the high demand (~530–810 Mt H_2 across scenarios) times the estimated life cycle emissions of producing hydrogen (>0.27–0.44 kgCO_2eq./kg H_2) is simply not compatible with net zero emissions by 2050. Using the Avoid-Shift-Improve paradigm [65,66], if we imagine that the movement towards 'clean' hydrogen is acting as the 'Shift' for new hydrogen use cases (or the 'Improve' for existing uses of hydrogen), and the use of the green and blue hydrogen represents the technological improvement (in which both electrolysis and blue hydrogen production are both largely unproven at scale), this leaves 'Avoid' as the remaining alternative. While the IEA has begun considering behavioural changes in its energy modelling, scientists have been calling for significantly greater considerations of degrowth and demand-side reductions in order to achieve climate goals [65].

If demand cannot be reduced, the further implication of these results is the need to appropriately define life cycle emission factors for 'clean' hydrogen, continuously updated with up-to-date climate science, similar, for example, to the science-based target initiative to ensure movement towards 'safe' development. In their Inflation Reduction Act, the U.S. government actually applied production tax credits based on the carbon footprint of the produced hydrogen [67], even incorporating the need to consider CCS and fugitive emission rates for blue hydrogen, which should be an effective measure, if enforced properly. While CertiHy's and the EU taxonomy's definitions of 'clean' hydrogen may be acceptable at current levels of demand, a ratcheting mechanism will be needed to ensure that if hydrogen consumption does indeed expand to the levels expected in the global energy models it does not consume a disproportionate amount of the remaining carbon budget over time.

This mechanism would have further consequences, however. As shown in Figures 2 and 3, for both green and blue hydrogen. For green hydrogen, currently, the life cycle emissions of solar-produced hydrogen would not even meet the EU Taxonomy's current definition of 'clean' hydrogen. Thus, under current operating conditions, green hydrogen on average would need to be produced disproportionately by wind, or the life cycle emissions of solar energy would need to further decrease for solar-produced hydrogen to enter the 'safe' space for hydrogen. For blue hydrogen, as Figure 2 shows, only under ideal operating conditions (near 100% CCS rates and near zero fugitive emissions) can blue hydrogen be considered 'safe'. This calls into question if blue hydrogen can even realistically be incorporated into net zero scenarios, with this notion supported by other recent studies [68], blue hydrogen is to be considered, at minimum, there should be a requirement of strict LCAs/environmental assessments to be performed on any site wishing to produce blue hydrogen and only under ideal conditions should operations be considered. This, of course, would affect the learning curves of such technologies if only used sparingly, thus further calling into question blue hydrogen's relevancy for a net zero transition.

Related to this subject, moving forward, energy system modellers and policymakers need to be more transparent [7], both in terms of emissions factors and as well as production technology used in models and policies. For example, the Australian hydrogen strategy states its assumed emissions factors for different hydrogen types, estimating zero emissions for green hydrogen and 0.71–0.76 $kgCO_2eq./kg\ H_2$ for blue hydrogen, which does not align with any of the LCAs performed for these types of hydrogen. This example highlights the need for transparency and the use of accurate and up-to-date LCA studies, such as those for blue hydrogen (and thus the need to be technology specific within the modelled results), because these factors significantly determine the environmental outcome of this transition. Chen and Lee [27] further identified this issue in their review of National Hydrogen strategies, where the pace at which low-carbon hydrogen would be transitioned and the stringency of the low-carbon definition was called into question in terms of how 'green' these strategies actually are.

This transparency and stringency on assumptions and the use of life cycle emissions in models, strategies, and certification schemes are paramount, as the widely varying results and emission factors in this work showed, especially due to the impacts of blue hydrogen, which depend on mostly yet unproven technologies. The absence of these aspects could mean the difference between a 'safe' transition and not.

In terms of achieving a 'safe' transition towards absolute sustainability, the reliance on technology extends beyond hydrogen. Researchers have called into question the reliance on the DACCS and BECCS, which represent further unproven technologies, in energy and climate global models, such as the IEA's and IPCC's [69–72]. These models should incorporate further demand-side solutions along with greater transparency. Lastly, this connects to recent calls to tie indicators and sectors to thresholds [73,74]. Particularly, if hydrogen is expected to meet 13–24% of global energy demand whilst overshooting carbon capture in 2050 (varying by scenario), an understanding of how 'safe' the hydrogen economy is becomes critical.

5. Conclusions and Policy Implications

This work recognizes its limitations. The estimates made are simplistic, largely due to lacking transparency in the global energy models used in the assessments reviewed. While this leads to uncertainty, the results show that from the scenarios in these energy models, with the broad ranges provided from the absolute best- and worst-case scenarios, regardless of the scenario, hydrogen is predicted to consume a disproportionate amount of the climate budget. Further, this study does not even consider the impacts of the massive infrastructure investment, both financial, energy, and material (and associated emissions) which would be required to support the hydrogen economy. Countries' hydrogen policies frequently cite the export potential of hydrogen (e.g., [75,76]), and the IEA has suggested public support of infrastructure is one of the most urgent tasks to support the hydrogen economy's development. There has been limited research on the environmental impacts of these infrastructures at scale and this is a field that also needs to develop. As an extension to this, with this work only considering supply-side configurations, it did not consider the various demand-side configurations which could lead to significantly different outcomes in terms of emissions. For example, if hydrogen saw large-scale use in transport, this could require a highly distributed system requiring greater infrastructure and associated emissions. This is an important area of further study. Additionally, this study could only look forward using current life cycle emission factors, which have their own uncertainties (see [77] for a taxonomy of such uncertainties), but as the global economy is decarbonized, many of the embedded impacts, such as emissions associated with the manufacturing of electrolysers and renewable energy technologies, are likely to be reduced. These predictions stand starkly against the reality of continued rising emissions, however, where in 2021, GHG emissions rose to their highest ever level [54]. As an extension of the challenges of making multi-decade projections, there are inherent uncertainties associated with technological development, particularly for nascent technologies such as electrolysis and CCS. Future studies could further investigate the influence of these uncertainties on the gauging of a safe space for the hydrogen economy. Additionally, how the hydrogen economy may unfold in terms of end uses is still largely uncertain [78], and thus the global energy models are also subject to significant uncertainty as well as the emissions associated with each of these pathways as previously discussed. Lastly, it should be noted that while this study benchmarks to limiting global warming to 1.5 °C, our window of opportunity of achieving this goal is quickly diminishing, and may perhaps already be out of reach, barring immediate drastic change unlikely to occur in the current political economy. Where the energy and other integrated assessment models (IAMs), such as the models considered here, use 1.5 °C as a political goal post, future studies may further want to consider scenarios such as 2 °C, which would change the results here by providing a greater carbon budget cushion for the hydrogen economy to rise [79].

There is also a significant lack of existing research on the social impacts of hydrogen due to its nascency and lack of existing examples [80], particularly at a systemic level as opposed to a specific end-use case study such as [81]. Researchers and the hydrogen community need to be proactive in assessing the energy justice impacts that the implementation of the global hydrogen economy may have. From energy poverty to global energy colonialism, with the varied role hydrogen may play across the many parts of society, it could bring with it social impacts and challenges [82]. These social issues are not insubstantial, and as noted by [83], if left unaddressed could lead to a lack of social buy-in and political push back which could hamper the hydrogen transition. Researchers [84,85] have taken a first approach in mapping the social energy injustices the expansion of the hydrogen economy may incur, but these early works need to be expanded upon as the transition to hydrogen accelerates.

The time pressure of addressing climate change should be noted, however, thus it is worth mentioning that while ensuring a 'just' transition is highly important, this work should be done in parallel to avoid potentially slowing progress towards a net-zero future [86]. This is particularly true for energy systems which tend to be slow moving and resistant to change [87].

Lastly, connected to the need to avoid demand is the metaphorical 'water' that we swim in of assumed global domestic product (GDP) growth. The need to degrow our economies if humanity hopes to achieve a 'safe' and 'just' space is becoming increasingly apparent [72], and with the only model which provided GDP numbers, the IEA for their net-zero pathway estimated a 3.16% compounded annual GDP growth rate from 2020–2050 [9]. Thus, even as the IEA models a net zero pathway, global GDP growth remains a constant assumption. While the degrowth paradigm faces its challenges, GDP's link to energy use has been shown, and while there has been some minor decoupling, it is clear that this is not happening fast enough [88], and using hydrogen as part of a larger technological silver bullet to solve the climate crisis may not be sufficient. An interesting research avenue moving forward would be to interpret how various degrowth pathways could influence the hydrogen economy and how such changes would influence alignment with safe development. Further, estimates on what level of degrowth would be required to achieve a safe hydrogen economy could be explored.

To conclude, this work is not suggesting that all use of hydrogen is bad. Hydrogen's expanded use in models is because it represents a shift from a more emission-intense alternative or an improvement of an existing use. Rather, it is a recognition that the transition in its current state is unaligned with absolute sustainability and that a "safe" development guideline is needed. What this study aims to suggest is that the demand for hydrogen should not be promoted to unsustainable levels for its own sake. Rather, the hydrogen economy should identify the most beneficial use cases of low-carbon hydrogen from environmental, social, and economic perspectives that will allow for a "safe" and "just" development of the hydrogen economy. As stated in Van de Graaf et al.'s [40]'s work, "The technologies and infrastructures underpinning a hydrogen economy can take markedly different forms, and the choice over which pathway to take is the object of competition between different stakeholders and countries." The pathways selected can lock us into certain unsustainable models if they are not carefully monitored and controlled, and thus, we need to choose carefully.

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