

Assessing the Environmental Impact of Global Hydrogen Supply through the Lens of Planetary Boundaries

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ABSTRACT

Hydrogen is increasingly recognized as a crucial energy carrier for a low-carbon future. However, most studies on clean hydrogen production devote limited attention to the entire supply chain. This study evaluates the sustainability of 800 combinations of hydrogen production and transportation methods, comparing their environmental impacts against the geophysical limits defined by the Planetary Boundaries framework. Findings reveal that no supply chain alone can make the current economy sustainable, yet powering water electrolysis with bioenergy and carbon capture and storage can meet the CO₂-based planetary boundaries. The analysis also underscores the need for decarbonization efforts in the hydrogen transportation sector, as certain options could offset the benefits of clean hydrogen production.

Keywords: Life Cycle Analysis, Planetary Boundaries, Absolute environmental sustainability, Hydrogen

INTRODUCTION

Most of current hydrogen production is centralized, with large-scale hydrogen plants, often located near natural gas reserves or industrial hubs, dominating global production. However, as global decarbonisation efforts accelerate and hydrogen is increasingly recognised as a crucial energy carrier for the transition to a low-carbon future, decoupling of production and demand become more likely. Regions with abundant renewable energy resources are positioned to produce green hydrogen at lower costs, while other industrialized regions have high hydrogen demand but limited local production capacity.

This potential paradigm shift is not yet reflected in the literature, where most research efforts still focus on hydrogen production alone. Few studies have examined the complete hydrogen supply chain, integrating both production and transportation. This leaves unanswered important questions about the real impact of large-scale hydrogen production, which can hamper a rapid transition towards a global hydrogen economy.

In addition, recent life cycle assessment (LCA) studies for hydrogen production and end uses are mostly limited to benchmarking alternatives. While these studies provide valuable insight regarding the best performing alternatives, they do not address the fundamental question

of whether said options are sustainable in absolute terms.

To address this gap, we investigate the sustainability of different technologies for hydrogen production and transportation in a global context, comparing the impacts produced by multiple supply chain alternatives against the geophysical limits provided by the Planetary boundaries (PB) framework [1]. PBs are safe environmental limits within which humanity can operate to ensure the stability and resilience of Earth's systems. Each boundary is associated with quantitative limits on specific control variables that help monitor its state. Crossing these boundaries increases the risk of destabilizing critical processes that regulate the planet, potentially leading to irreversible environmental changes. Hence, comparing impacts of hydrogen supply chains against PBs is crucial to properly assess the potential consequences of adopting a hydrogen economy for the planet.

METHODOLOGY

Hydrogen Supply Chain Pathways

The present study evaluates the environmental performance of various hydrogen supply chains (i.e., production and transportation) options on a global scale. Specifically, we base our analysis on the 2021 hydrogen demand data provided by the International Energy

Agency (IEA) [2], which accounts for a total of 94 Mt. This demand is distributed across six regions: Europe (EU), China (CN), India (IN), the Middle East (ME), the United States (USA), and the Rest of the World (RoW).

We analyse 32 hydrogen production methods (see Figure 1a), including steam reforming using biogas or natural gas (Business-As-Usual (BAU)) as feedstock, as well as water electrolysis (WE) powered by various energy sources, such as bioenergy with carbon capture and storage (BECCS) or wind energy. We also explore the potential of producing hydrogen from waste materials, such as plastic waste, aluminium scrap, rice husks, and residues from other processes, using methods like gasification, aluminium combustion, or dark fermentation.

In addition, we model hydrogen transportation with the aim of understanding how the introduction of this activity would affect the Earth System in terms of PBs. This requires tracking (i) hydrogen state, and (ii) the transportation mean used of each alternative.

For the former, three options are considered: compressed hydrogen gas, liquid hydrogen, and hydrogen chemically bonded to another compound to form a stable liquid, the so-called Liquid Organic Hydrogen Carrier (LOHC). LOHCs are molecules that can absorb and release hydrogen through hydrogenation and dehydrogenation reactions, behaving as a storage media for hydrogen transportation. Hydrogen transportation as a LOHC can be addressed in two different ways. On the one hand, a linear transportation of the LOHC, which, upon dehydrogenation, results in the transportation of two compounds, hydrogen and the precursor of the corresponding LOHC, using the same transport. Alternatively, the precursor could be recirculated for reuse, reducing this way its overall consumption. This second option is considered for two compounds: dibenzyl toluene (DBT) and toluene.

For the transportation mean, hydrogen can be transported in any of the previous state-form alternatives. This can be done *via* pipeline, truck, and shipping. However, not all hydrogen state and transportation method combinations are viable. For instance, transporting liquid hydrogen *via* pipeline is highly energy-intensive due to the extreme cooling required to maintain its liquid state. Additionally, pipelines would require expensive insulation and frequent maintenance to prevent ice formation around pipes, valves, and vents. Therefore, this option is excluded. Similarly, compressed hydrogen *via* shipping is less feasible than liquid hydrogen, as the latter minimizes boil-off losses and requires less volume and weight. As a result, the three transportation means are available for all the LOHCs (i.e., $3 \cdot (5+2) = 21$), but only two alternatives are considered for the other hydrogen-state forms ($2 \cdot 2 = 4$). This results in a total of 25 transportation options, which, combined with the 32 production methods, yield a total of 800 alternative hydrogen supply

chains. For simplicity, this study assumes that hydrogen production and transportation, over 500 km, occur within the same region where demand arises. However, a sensitivity analysis on transport distance is also performed to ascertain the potential influence of this parameter in the assessment.

LCA and Planetary Boundaries

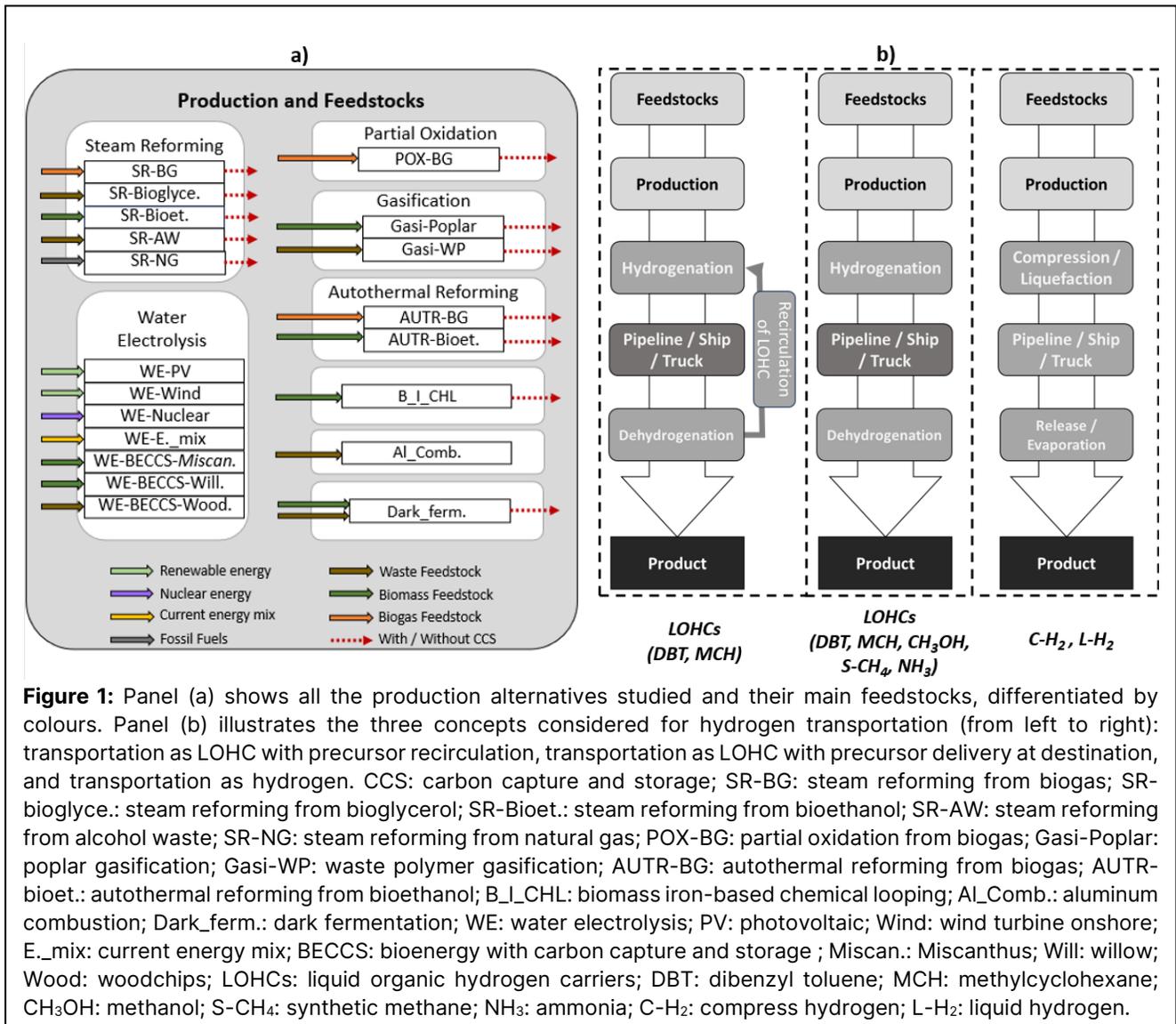
Next, the resulting 800 alternatives are assessed using the Planetary Boundaries-Life Cycle Impact Assessment (PB-LCIA) framework, an absolute environmental sustainability assessment (AESA) method, bridging conventional LCA principles with the concept of PBs. This requires following the four interconnected phases of the general LCA methodology.

In the first phase, the scope and goal of the study are defined. In this case, the goal is to quantify the absolute environmental sustainability level of different hydrogen supply chain alternatives, adopting an attributional approach with a cradle-to-gate perspective, i.e., considering processes from raw material extraction to hydrogen production and transportation. The functional unit is the annual hydrogen demand in 2021 for each region provided by the IEA, measured in million tonnes per year.

In the second phase, primary inputs and outputs — energy, raw materials, byproducts, and emissions— flowing in and out of the system (i.e., crossing its defined boundaries) are quantified. To this end, mass and energy balance information is gathered from previous studies. Then, this information is combined with the corresponding background activity data from ecoinvent v3.8 to calculate the so-called life cycle inventories (LCIs). This procedure was automated using the Activity Browser interface for Brighway2 open-source LCA software. In all cases, the “Allocation at the point of substitution” (APOS) system model was used.

Since hydrogen production and transportation are assumed to take place within the same region, the study accounts for location-specific environmental impacts. However, the regional classification in the ecoinvent v3.8 database does not align directly with the IEA regionalization, from which hydrogen demand data are sourced. To address this, distinct ecoinvent lumped regions (e.g., Rest of Europe (RER)) are used to model background activity impacts. When specific data for an activity is unavailable at the lumped-region level, data from a representative country within that region (e.g., Germany (DE)) are used instead. If no country-specific data are available, “Rest of the World” (RoW) data are used.

The third phase of the LCA involves assessing the damage produced by the LCIs in different environmental categories. In this case, ten control variables referring to eight Earth-System processes related to the PBs are considered. The PB-LCIA framework is used to express LCIs as impacts caused on the corresponding control



variables by means of appropriate characterisation factors (CF). This can be expressed in mathematical terms as follows. The environmental impact caused by alternative s on control variable b ($EI_{b,s}$) is calculated with Eq. (1):

$$EI_{b,s} = \sum_f LCI_{s,f} \cdot CF_{b,f} \cdot FU \quad \forall b, s \quad (1)$$

where $LCI_{s,f}$ represents the quantity of elementary flow f associated with the production and/or supply of one kilogram of hydrogen in alternative s , $CF_{b,f}$ is the CF translating the impact of one unit of elementary flow f into control variable b , and FU denotes the functional unit in consistent units (i.e., kilograms of hydrogen per year). CFs developed by Ryberg et al. [3] are employed for all the control variables studied expect for BII, for which the CFs by Galán-Martin et al. [4] are used.

In the fourth phase, results are interpreted, and recommendations are made. This is where the PBs framework demonstrates its full usefulness, as it provides

quantitative limits to ascertain whether the activity under analysis can be deemed sustainable or not. To this end, results are compared against absolute limits derived from the PB framework, which defines the level to which principal Earth-system processes can be disturbed before triggering irreversible damage. We note that some Earth-system processes have clear thresholds beyond which critical changes would happen, while others do not. However, even when no precise tipping point exists, increasing stress can still lead to cumulative and potentially irreversible damage, triggering cascading effects on other systems. To address this, an uncertainty zone is defined around each control variable boundary, recognizing that the exact point of irreversible change is not always clear.

Additionally, the planet itself naturally contributes towards each control variables; this is called the natural background level (NBL). Hence, the available 'environmental budget' for human activities, the so-called safe operating space (SOS), is obtained by subtracting the

NBL from the corresponding threshold of the PB: here, the limit between the safe and the uncertainty zone.

On the other hand, PBs are defined at a global scale, but this study assesses only a single sector. To overcome this mismatch in scope, previous studies have employed downscaling methods, although this is a controversial approach that can yield varying conclusions depending on the specific downscaling methodology used. To avoid this, we simulate the global anthropogenic impact of the whole economy (IMP^{GLO}) that would result from replacing the BAU scenario for the hydrogen sector ($IMPT^{BAU}$) by each of the 800 alternatives for hydrogen production and transportation ($IMPT^{ALT}$).

$$IMP_{b,s}^{GLO} = IMP_b^{CUR} - IMP_b^{BAU} + IMP_{b,s}^{ALT} \quad \forall b, s \quad (2)$$

Here, $IMP_{b,s}^{GLO}$ provides the global impact of the whole economy on control variable b after substitution of alternative s ; IMP_b^{CUR} corresponds to the current impact of the whole economy on control variable b ; IMP_b^{BAU} is the impact of the BAU scenario for hydrogen supply on control variable b ; and $IMP_{b,s}^{ALT}$ is the impact of hydrogen supply alternative s on control variable b .

Finally, in order to ascertain whether a scenario is environmentally sustainable in absolute terms, the PB footprint (PBF) [6] is calculated by comparing the (predicted) global anthropogenic environmental impact $IMP_{b,s}^{GLO}$ with the SOS, as shown in Eqs. (3-4).

$$LT_{b,s}^{GLO} = \begin{cases} 0 & \text{if } \frac{IMP_{b,s}^{GLO}}{SOS_b} < 1 \\ \frac{IMP_{b,s}^{GLO}}{SOS_b} & \text{otherwise} \end{cases} \quad \forall b, s \quad (3)$$

$$PBF_s = \frac{\sum_b LT_{b,s}^{GLO}}{|B|} \quad (4)$$

Here, the global level of transgression ($LT_{b,s}^{GLO}$) is given by the quotient between the global anthropogenic impact $IMP_{b,s}^{GLO}$ (for control variable b under alternative s) and the SOS for each control variable b (SOS_b). PBs not transgressed after sector substitution, are assigned a $LT_{b,s}^{GLO}$ value of 0 is assigned, thus prioritising solutions that can meet multiple boundaries concurrently. Finally, the summation of the transgression level for each control variable b (under alternative s) is divided by $|B|$, which corresponds to the number of control variables considered (ten in this study). This is equivalent to assuming equal weights regardless of the transgression level, i.e., all control variables are deemed equally important.

RESULTS AND DISCUSSION

To provide some context, we start by analysing the current impacts of the global economy onto the PBs (Figure 2a). This is a relevant analysis since, arguably, already-transgressed boundaries should be prioritized

when designing alternative systems and technologies. As can be seen in the figure, only four PBs are currently met: SOD, OA, FWU and AAL (see Figure 2 caption for acronyms). From the remaining control variables, four lie in the uncertainty zone (i.e., CO₂-conc., P flow, LSC and BII), while the other two are severely transgressed, reaching the high-risk zone.

Currently, hydrogen is responsible for more than 15% of the impacts incurred at global scale on CO₂-base control variables (En-Imb., CO₂-conc., and OA, see black labels in the figure), while showing minor contributions (i.e., below 5%) to impacts on AAL and BII, and smaller than 0.01% in the remaining control variables. However, when hydrogen impacts are compared against the SOS (green labels), it can be seen that global hydrogen supply represents 39%, 40%, and 13% of the maximum impacts allowed at the global level in En-Imb., CO₂-conc., and OA, respectively. This reveals a concerning situation since it is hard to envision that the remaining economic sectors can successfully operate within the remaining SOS for these control variables. The situation is even more worrisome when considering that some of the PBs associated with these control variables have already been crossed at the global level (see Figure 2a). On the other hand, small contributions are observed towards the remaining control variables, all of them more strongly linked to other anthropogenic activities, mainly agriculture [5]. This situation might worsen in the coming years due to the expected increase in hydrogen demand.

We next turn our attention to the alternatives studied (Figure 2b), finding that only 205 out of the 800 hydrogen supply chains considered exhibit a lower PBF than the BAU scenario. As an example, the BAU scenario, predominantly based on steam reforming from natural gas, remains a better option than WE given that the current electricity mix is still largely based on fossil fuels.

There is no hydrogen supply chain that alone can make the current economy sustainable: additional efforts will be required from other sectors. The alternative with the lowest PBF (0.90) is WE-BECCS with Miscanthus, which meets the SOS limits for the CO₂-base control variables. However, growing biomass feedstock exerts increasing pressure on the Biodiversity Intactness Index (BII) due to land use impacts, though this boundary remains within the uncertainty zone (from 268% to 288% of the SOS). Additionally, biomass combustion contributes to NMVOC emissions, increasing pressure on the Atmospheric Aerosol Loading (AAL) boundary, but without exceeding the uncertainty zone (from 66% to 86%).

Al_Comb. emerges as a slightly better option production than WE with PV and wind turbines, primarily due to avoided impacts associated with aluminium scrap management. However, this effect shows asymmetric contributions across regions (results not shown owing to space limitation). Negative impacts (i.e., lower than zero)

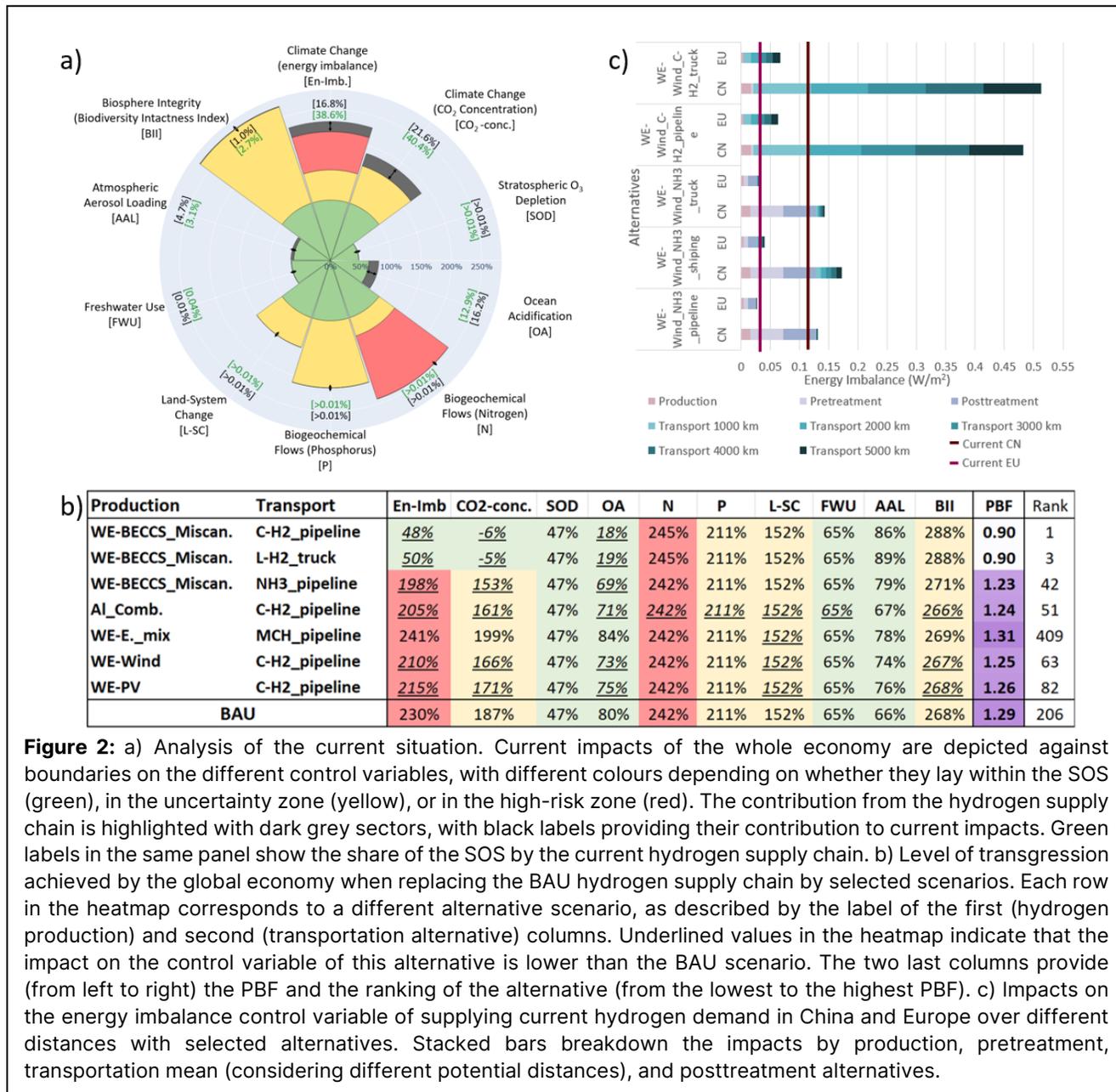


Figure 2: a) Analysis of the current situation. Current impacts of the whole economy are depicted against boundaries on the different control variables, with different colours depending on whether they lay within the SOS (green), in the uncertainty zone (yellow), or in the high-risk zone (red). The contribution from the hydrogen supply chain is highlighted with dark grey sectors, with black labels providing their contribution to current impacts. Green labels in the same panel show the share of the SOS by the current hydrogen supply chain. b) Level of transgression achieved by the global economy when replacing the BAU hydrogen supply chain by selected scenarios. Each row in the heatmap corresponds to a different alternative scenario, as described by the label of the first (hydrogen production) and second (transportation alternative) columns. Underlined values in the heatmap indicate that the impact on the control variable of this alternative is lower than the BAU scenario. The two last columns provide (from left to right) the PBF and the ranking of the alternative (from the lowest to the highest PBF). c) Impacts on the energy imbalance control variable of supplying current hydrogen demand in China and Europe over different distances with selected alternatives. Stacked bars breakdown the impacts by production, pretreatment, transportation mean (considering different potential distances), and posttreatment alternatives.

on CO₂-based control variables are achieved in all regions except in India, where the reliance on fossil fuels for electricity generation offsets the benefits of aluminium recycling.

Regarding transportation (Figure 2b), C-H₂ via pipeline is the most favourable option as it eliminates the need for conversion (e.g., hydrogenation-dehydrogenation reactions for LOHCs) or conditioning (e.g., liquefaction for L-H₂). For example, certain LOHCs such as DBT would transgress planetary boundaries like OA, while others like CO₂-concentration could shift from the uncertainty zone to the high-risk zone (results not shown). The AAL control variable also increase for all cases using LOHCs, specially for DBT, MCH, and CH₃OH. This is primarily due to the energy-intensive nature of

pretreatment processes such as compression, liquefaction, and hydrogenation.

In CO₂-based control variables, as well as in BII, S-CH₄ and NH₃ alternatives show the highest contributions from post-treatment, highlighting this stage as a key bottleneck in these transportation pathways. Notably, if S-CH₄ and NH₃ were directly used as fuels (i.e., avoiding H₂ regeneration) their contribution from transport would almost be on par with those from C-H₂ or L-H₂. In addition, this would have the added benefit of avoiding the need to update the transport infrastructure, as required for C-H₂. This suggests that S-CH₄ and NH₃ could serve as competitive alternatives to hydrogen in energy applications, providing comparable performance while reducing transport and infrastructure needs. This is only a viable

option in energy applications and not in cases where hydrogen is used as a chemical feedstock.

Finally, the largest contribution in the supply chain depends on the combination of production and transportation alternatives. For instance, in purple hydrogen (WE-nuclear), electrolysis contributions range from 0.5% to 37.5%, depending on the transportation method. Conversely, in alternatives such as WE-BECCS, the negative impacts from production are substantial enough to offset all positive transportation impacts. On the other hand, transport distance and regional factors are also crucial parameters. As an example (Figure 2c), we find that WE-wind combined with C-H₂ in China is a better alternative than BAU only for distances below 1,000 km, due to the energy required for hydrogen recompression every 250 km. For context, the breakeven distance for Europe is 2,500 km. Therefore, hydrogen decarbonization must be accompanied by simultaneous electricity mix decarbonization, which may follow different pathways and timelines across regions.

CONCLUSIONS

Our results uncover the potential threats of maintaining the current hydrogen supply chain, which requires an excessive environmental budget: standalone, almost 40% of the Safe Operating Space in some control variables. Shifting Natural gas Steam reforming with Carbon Capture Storage or green hydrogen could reduce the damage to critical CO₂ control variables, leaving room for other hard-to-abate economic sectors to operate. However, decarbonisation efforts such as Water Electrolysis combined with Bioenergy with Carbon Capture Storage could still worsen Biodiversity Intactness Index or Nitrogen flows. In addition, recycling waste (e.g., aluminium scrap or plastic waste) to produce hydrogen can mitigate environmental burdens without jeopardising the Biodiversity Intactness Index (as Water Electrolysis combined with Bioenergy with Carbon Capture Storage does), or threatening the resources of critical materials required for the construction of electrolyzers, photovoltaic panels, or wind turbines. Finally, when formulating policies for the hydrogen economy, these must also consider transportation means, as they could negate the efforts made in hydrogen production. Overall, this highlights the need to optimize hydrogen supply chains holistically.

ACKNOWLEDGEMENTS

This publications and other results have the support of the predoctoral program AGAUR-FISDUR (2023 FISDUR 00189) of the Secretariat of Universities and Research of the Department of Research and Universities of the Generalitat of Catalonia and the European Social Plus Fund. The authors acknowledge grants PID2021-

1235110B-C33, and PID2021-124139NB-C22 funded by MCIN/AEI/10.13039/501100011033 and by “FEDER, UE”, grant TED2021-129851B-I00 funded by MCIN/AEI/10.13039/501100011033 by the European Union NextGenerationEU/PRTR, and grant CNS2023-144890 funded by MICIU/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR.

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