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Life Cycle-Based Environmental Assessment of Hydrogen Production Mixes Projected in the Hungarian Hydrogen Strategy Using the Environmental Footprint Methodology

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Hydrogen (H_2) is increasingly cited as a key element of future sustainable energy systems. Environmental assessment of H_2 production is gaining importance in meeting climate goals. While current literature mainly focuses on reducing CO_2 emissions, other life cycle impacts – such as effects on ecosystems, human health, and resource use – are often underestimated. In the Hungarian context, this study represents the first attempt to estimate the environmental impacts of the national Hydrogen Strategy. This study aims to fill this gap through a quantitative environmental evaluation of hydrogen production pathways projected in the Hungarian Hydrogen Strategy. Based on life cycle assessment (LCA) using the Sphera database, three major production technologies were modelled: steam methane reforming (grey), reforming with carbon capture (blue), and solar PV-based electrolysis (green). Results show that the total environmental burden of hydrogen production in Hungary could be halved by 2050 compared to 2020, while the specific carbon footprint of H_2 production could be 75 % lower than today. However, this projection excludes expected efficiency improvements, as much of the future capacity has yet to be built.

1. Introduction

The global pursuit of decarbonisation has intensified the importance of exploring sustainable energy solutions, among which hydrogen is regarded by some experts as a promising energy carrier. LCA is a standardised methodology designed to systematically evaluate and compare the environmental impacts associated with the full life cycle of hydrogen production methods. The environmental profiles of hydrogen production vary depending on the primary energy source used, and the sustainability of different production technologies has become a central issue in both scientific literature and policy debates. In this context, LCA-based analyses may serve as a valuable tool for clarifying controversial aspects.

Hungary's total energy supply remains dominated by fossil fuels, with oil and oil products accounting for about 32 % and natural gas for around 31 % of the total energy supply in 2024; nuclear energy contributes approximately 18 %, while renewables together provide the remaining share (International Energy Agency, 2024)Click or tap here to enter text.. Regarding climate performance, approximated domestic GHG emissions were ~59.8 $MtCO_2$-eq in 2022, while preliminary 2023 data indicate ~54.3 $MtCO_2$-eq (48.5 $MtCO_2$-eq net after LULUCF) (HungaroMet – Hungarian Meteorological Service, 2024).Click or tap here to enter text. Thesez figures frame the baseline against which the projected hydrogen pathways are evaluated in this study.

2. Literature Review

The primary methods of hydrogen production can be classified into three main categories: fossil fuel-based processes, biomass-based methods, and water electrolysis. Traditionally, hydrogen is produced via steam methane reforming (SMR), while similar technologies include hydrocarbon pyrolysis, coal gasification, partial oxidation of liquid hydrocarbons, and autothermal reforming—a combined process of steam reforming and

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partial oxidation. Although these methods are economically viable, they result in significant carbon dioxide emissions and other environmental impacts due to reliance on fossil fuels (Chen et al., 2008). Renewable energy sources enable hydrogen production from biomass-derived compounds and water (Megía et al., 2021). Hydrogen production technologies are categorised by colour labels based on the primary energy sources used, associated costs, emissions, and technological specifics (Arcos and Santos, 2023). Grey hydrogen refers to hydrogen produced by steam methane reforming, partial oxidation of liquid hydrocarbons, or autothermal reforming. If carbon dioxide produced during grey, black, or brown hydrogen production is captured using CCS/CCUS technologies, the resulting product is termed blue hydrogen (AlHumaidan et al., 2023). Similarly, turquoise hydrogen, produced via methane pyrolysis, involves permanent sequestration of the solid carbon byproduct. Achieving carbon neutrality for turquoise hydrogen requires renewable energy sources for reactor heating (Diab et al., 2022). Aqua hydrogen is an emerging technology that extracts hydrogen from oil sands or oil fields through subsurface processes, achieving low-cost, carbon-neutral production (Yu et al., 2021). Green hydrogen, produced by water electrolysis using renewable energies such as wind or solar power, represents the most environmentally friendly option, albeit currently the most expensive. Green hydrogen can also be produced from biomass using renewable energy inputs. Yellow hydrogen is obtained by water splitting using solar power or grid electricity, with associated emissions dependent on the energy mix. Pink hydrogen is generated from nuclear energy, whereas purple hydrogen involves nuclear heat, partly used for electricity generation and partly for thermochemical hydrogen production. Red hydrogen results from high-temperature thermal electrolysis using nuclear or concentrated solar energy. Gold hydrogen is produced by direct solar-to-hydrogen conversion technologies utilising photovoltaic cells. Orange hydrogen is generated from water electrolysis powered by biomass or municipal waste gasification. Finally, white hydrogen, also known as natural hydrogen, occurs naturally via geological processes (Arcos and Santos, 2023).

Future global energy production analyses generally suggest meeting growing demand through diversified energy mixes, including renewable and sustainable sources (Johnston et al., 2005). The EU's REPowerEU plan targets producing 10 Mt of renewable hydrogen domestically and importing an additional 10 Mt (European Commission, 2023). Hydrogen's strategic role in the green transition underlines the necessity of developing targeted hydrogen strategies. By May 2024, 46 national hydrogen strategies had been published globally, involving at least 74 countries. Japan was the first to publish its hydrogen strategy in December 2017, followed by the EU as the sixth entity in July 2020, and Hungary as the sixteenth in June 2021 (Ediger, 2019). The EU Hydrogen Strategy outlines establishing 6 GW of electrolyser capacity by 2024, corresponding to 1 Mt of green hydrogen production, expanding to 60 GW (approximately 10 Mt) by 2030 (The Engineering ToolBox, 2003). In 2023, the European Commission adopted rules and definitions for Renewable Fuels of Non-Biological Origin (RFNBO), essential for implementing both the EU Hydrogen Strategy and the REPowerEU plan (European Parliament and Council of the European Union, 2023). Hungary's hydrogen strategy presents ambitious projections for establishing a domestic hydrogen economy, with projected hydrogen production distributions and quantities shown in Table 1. It is evident from Table 1 that while hydrogen production is projected to increase by only 4 % between 2020 and 2040, a significant rise of 48.5 % is anticipated between 2040 and 2050. The methods utilised for hydrogen production fundamentally influence its sustainability profile; therefore, their applicability and environmental impacts require a comprehensive LCA, encompassing stages from raw material extraction to final use. Mitigation of CO_2 emissions has become a central issue. Despite numerous international scientific articles addressing the life cycle analysis of various hydrogen production methods, the emphasis predominantly remains on unit CO_2 emissions, with other environmental impact categories often overlooked or entirely omitted from evaluations. The holistic approach employed in this study enables a thorough examination of trade-offs among various environmental impact categories related to different hydrogen production technologies, under both current and future scenarios. This study aims to address this research gap by providing comprehensive environmental assessments of hydrogen production mixes projected in the Hungarian Hydrogen Strategy, offering additional insights into the environmental burdens associated with hydrogen production.

Table 1: Projected Domestic Industrial Hydrogen Production (kt) (Based on Hungarian Hydrogen Strategy, own edited)

	2020	2030	2040	2050
Grey hydrogen	160	138	22	0
Green hydrogen	0	20	126	107
Blue hydrogen	0	5	19	141
TOTAL	160	163	167	248

3. Methods

3.1 Life cycle assessment

By default, LCA involves identifying and evaluating material and energy flows throughout the entire lifecycle of a given product (or service). By assessing the inputs and outputs across all life stages, LCA systematically quantifies the associated environmental impacts. The LCA methodology, standardised by ISO 14040 and ISO 14044, consists of four distinct phases:

Goal and Scope Definition: The first step involves establishing the purpose of the analysis, clearly defining system boundaries, selecting the functional unit, and choosing an appropriate impact assessment methodology.

Life Cycle Inventory (LCI): The second phase of the LCA is compiling the lifecycle inventory, which involves quantifying the materials, energy inputs, and environmental emissions (outputs) associated with either the entire lifecycle or specific lifecycle stages of the system under investigation.

Life Cycle Impact Assessment (LCIA): In the third phase, the collected inventory data are processed and assessed to translate these values into relevant impact categories, facilitating a clearer understanding of their environmental significance.

Interpretation: The final phase of the LCA process involves interpreting and critically evaluating the findings derived from the lifecycle inventory and impact assessment phases, enabling informed decision-making and policy support.

3.2 Goal and Scope Definition, LCI

This study aims to explore the extent of environmental impacts associated with different hydrogen production mixes projected in the Hungarian Hydrogen Strategy. The research evaluates the cumulative environmental burdens of the 2020 hydrogen production mix and the projected hydrogen production mixes for the subsequent three decades. Hydrogen is assessed as an energy storage medium, comparing various production methods. The reference unit is 1 kg of low-pressure H_2 at the production site, excluding additional compression, storage, or transportation. This paper follows a cradle-to-gate boundary from feedstock extraction to hydrogen at the plant gate. Included: upstream supply chains for natural gas and electricity, plant utilities, and the core production steps (NG-SMR, NG-SMR-CCS, PV-electrolysis). Excluded: downstream compression, storage, distribution and end-use, which are common across scenarios. Capital goods are represented in the Sphera background datasets. For the blue pathway, CO_2 capture and on-site conditioning/compression are included; CO_2 transport and storage beyond the plant gate are out of scope. Three models were developed in alignment with the Hungarian Hydrogen Strategy, with impact assessment conducted according to the forecasted domestic industrial hydrogen production presented in Table 1. The analysis utilised Sphera – LCA for Experts software and associated Sphera databases. In the grey hydrogen model, hydrogen production via natural gas-based steam methane reforming (SMR) was considered. The blue hydrogen model expanded the grey hydrogen model by incorporating Carbon Capture and Storage (CCS) technology, with CCS parameters modelled based on data from the literature (Li et al., 2022). As the Hungarian Hydrogen Strategy did not explicitly define the technology corresponding to the "low-carbon hydrogen" category, our study considers natural gas-based SMR coupled entirely with CCS technology as blue hydrogen. For both grey and blue hydrogen models, a country-specific natural gas consumption mix was applied, comprising domestically produced gas and imports from relevant countries, specifically 12.29 % domestic and 87.71 % Russian gas. The Hungarian Hydrogen Strategy emphasises long-term green hydrogen production primarily from renewable sources, especially photovoltaic (PV) solar energy, but also considers possibilities for nuclear-based and carbon-free grid electricity hydrogen production. Given this declaration and the absence of specific distribution data, and considering that nuclear and carbon-free electricity are not classified as green hydrogen in the literature, the green hydrogen model exclusively utilised solar PV as the electricity source.

Grey hydrogen is modelled as NG-SMR; the reformer thermal efficiency is ~79.8 % and product H_2 purity ≥99.995 %, 10 bar outlet pressure. Blue hydrogen extends NG-SMR with CCS; the whole-plant CO_2 capture rate is assumed at 90 % (reference-case value widely used in IEAGHG/IEA assessments). Green hydrogen uses mono-Si PV electricity supplying PEM electrolysis; the database main process assumes ~62.5 % electrolysis efficiency at 14 bar, with H_2 purity ≥99.995 % at 10 bar. Process water use for PEM is ≈25.7 L/kg H_2. Country-specific natural-gas supply mix and electricity mixes are taken from the Sphera background (Hungary NG mix modelled 12.29 % domestic / 87.71 % imported Russian). Although energy release via combustion marks the end-of-life phase for hydrogen across all three models, this stage was not analysed due to its uniformity across scenarios. Renewable energy production does not directly emit CO_2, yet necessary infrastructure and manufacturing processes, such as those associated with PV installations, may entail indirect environmental impacts. It is crucial to recognise that most hydrogen production capacities will be developed in the future, enabling efficiency improvements, the introduction of new technologies, and supply chain optimisations, potentially reducing environmental impacts.

3.3 Life Cycle Impact Assessment

For LCA, the Environmental Footprint (midpoint) impact assessment method was applied, updated from EF 3.0 to EF 3.1 by the Commission based on work by the EF Technical Advisory Board and various expert groups. During this update, new characterisation factors for six impact categories and new normalisation factors for eight impact categories were tested and validated. In 2021, the IPCC published new characterisation factors for climate change (IPPC, 2021), which were implemented in the model. Updating these characterisation factors necessitated recalculating normalisation factors. Inputs and outputs from the life cycle inventory were grouped into 16 midpoint impact categories, each with its specific metric. The updated normalisation factors published by the EU in 2023 (Andreasi et al., 2023) were employed for normalisation. Subsequently, the normalised dimensionless values were weighted according to literature recommendations (Andreasi et al., 2023) to reflect the relative importance of impact categories. By applying the recommended normalisation and weighting, impacts were consolidated into a single comparable metric. The aggregate environmental performance score, representing environmental performance, was generated by summing these normalised weighted impact categories (Andreasi et al., 2023). The Environmental Footprint (EF) methodology version 3.1, adopted by the EU, is an increasingly recognised standard in LCA, especially for supporting EU policies and achieving comparable results. Background processes (fuels, power, materials) reflect EU/Hungary conditions with ~2021–2023 temporal representativeness from the Sphera database. Capital goods (e.g., reformer/CCS units, PV modules, electrolysers) are included as represented in the background datasets. We apply no co-product credits (e.g., O_2 from electrolysis) and no avoided-burden credits for CO_2 transport/storage beyond the captured stream—a conservative choice that preserves comparability across pathways. The single score is reported alongside disaggregated category results; key parameters are covered by sensitivity checks elsewhere in the paper.

4. Results

After the applied normalisation and weighting procedures, dimensionless EF scores were obtained. The impact categories were grouped according to the ultimate recipients of impacts, namely: climate change, ecosystems, human health, and resources. In the following sections, the results are evaluated based on these endpoint categories. Figure 1 illustrates the total CO_2-equivalent emissions associated with the hydrogen production mix in each target year. Based on the data, the carbon footprint of 1 kg H_2 produced in Hungary will decrease by around 75 % by 2050. Compared to 2020 levels, the total CO_2-equivalent emissions of the sector are projected to decrease by 9 % by 2030, 60 % by 2040, and 64 % by 2050, from 1.6 Mt CO_2e in 2020 to 0.6 Mt CO_2e in 2050 (Figure 1). This is despite the expected increase in hydrogen production in Hungary: by 2 % in 2030, an additional 2 % by 2040, and a 55 % increase by 2050 compared to the 2020 baseline (Table 1).

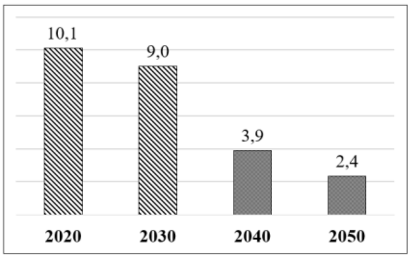

Figure 1: Projected specific carbon footprint of hydrogen production under the Hungarian Hydrogen Strategy (kg CO_2 eq. / kg H2), 2020–2050. (own compilation, based on own calculations)

Our results indicate that although climate change remains the dominant factor throughout the studied period, resource impacts notably increase from 2040 onwards, becoming dominant while the relative importance of climate change decreases. The other two impact categories also demonstrate notable increases, particularly by 2040 and 2050.

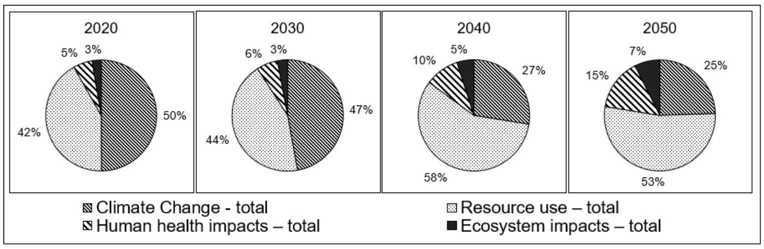

Figure 2: Distribution of impact category scores across key affected systems based on the projected domestic hydrogen production mix (own compilation, based on own calculations)

Figures 1 and 2 might initially suggest a complete shift of the environmental burden from climate change to other impact categories. Adopting a comprehensive perspective that includes the total environmental burden is crucial for accurately assessing the overall anticipated environmental impacts of hydrogen production.

Figure 3 clearly illustrates the projected temporal decrease in cumulative impacts based on Hungary's anticipated hydrogen production mix. In this figure, various impact categories are represented as stacked columns for each period, symbolising cumulative environmental burdens. Overall environmental impacts decrease by 50 % over the period, reflecting a reduction in fossil fuel dependence and the greening of hydrogen production technologies. Individual impact categories contribute differently to these changes, effectively demonstrating both direct and indirect impacts of technological transitions. Despite climate change-related impacts dominating in 2020, they decline by 77 % by 2050, attributable to the gradual phase-out of fossil-based hydrogen production (grey and blue hydrogen) and the expansion of green hydrogen. The impact associated with fossil resource use also decreases significantly—by 46 %—by 2050. However, some impact categories worsen over time. Acidification rises by around 75 %, and particulate matter nearly quadruples by 2050. Resource use, land use, and freshwater ecotoxicity also increase, highlighting trade-offs in decarbonisation and the need for a holistic life-cycle perspective when assessing low-carbon technologies.

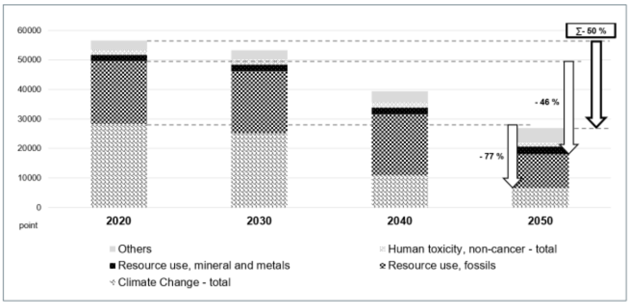

Figure 3: Distribution of impact category scores on resources as the final receptor, by scenario (own compilation, based on own calculations)

5. Conclusions

In summary, this study offers a novel contribution by being the first to conduct a forecasted LCA of Hungary's hydrogen production mixes, supporting the future development of the national hydrogen sector. The primary aim was to compare the environmental burdens associated with grey, blue, and green hydrogen production technologies based on projections for the 2020–2050 period. The modelling results confirmed that a decreasing share of grey hydrogen and the gradual greening of the hydrogen production mix lead to a reduction in overall environmental impact scores. Our findings quantitatively demonstrate that by 2050, the total environmental burden of Hungary's hydrogen production could be reduced by half compared to the 2020 baseline. This trend is attributable to both technological decarbonisation and the declining use of fossil energy sources. Comparing the forecasted scenarios for each decade, climate change-related impacts are projected to decrease by 11 % by 2030, 57 % by 2040, and 40 % by 2050 — amounting to a total reduction of 77 % between 2020 and 2050. It is important to note, however, that these results do not account for potential future technological innovations, which could further improve both efficiency and environmental performance. Overall, while the reduction in CO_2 emissions—a key impact category—is evident, not all environmental impacts decrease simultaneously. Although other categories contribute less significantly than climate change and fossil resource use, they should not be overlooked, especially where slight increases are observed. Fossil-based hydrogen production must be further phased out from an environmental perspective. Advancing green hydrogen production technologies remains essential, particularly in improving electrolysis efficiency and minimising water consumption. To accelerate the shift toward a greener hydrogen mix, effective economic incentives and environmental policy support are crucial. These measures should promote broader integration of renewable energy sources and foster investment willingness among market actors. Alongside climate mitigation, it is vital to monitor additional impact categories to ensure that progress in decarbonisation does not come at the expense of other environmental concerns. Awareness of both the benefits and trade-offs of hydrogen technologies must be raised among citizens, industry stakeholders, and policymakers. A more detailed investigation of the hydrogen production mix's life cycle is warranted—especially to uncover causal relationships among impact categories. Assessing the implications of technology integration at the full energy system level would be highly beneficial. Based on these results, it can be concluded that Hungary's hydrogen strategy represents a significant step toward a sustainable energy transition. However, to minimise environmental trade-offs, carefully considered technological and policy measures will be required.

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