Clean Hydrogen Partnership

European Hydrogen Sustainability and Circularity Panel

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Introduction to Hydrogen Sustainability

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List of Acronyms

Ammonia	NH3
Capital Expenditure	CAPEX
Carbon Border Adjustment Mechanism	CBAM
Carbon dioxide	CO2
Critical Raw Materials	CRM
Department of Energy	DOE
End-of-life	EoL
Environmental Footprint	EF
EU Emissions Trading System	ETS
European Hydrogen Sustainability and Circularity Panel	EHS&CP
European Network for Network Operators of Hydrogen	ENNOH
European Network of Transmission System Operators for Electricity	ENTSO-E
European Network of Transmission System Operators for Gas	ENTSO-G
European Union	EU
Gigawatt	GW
Greenhouse gas	GHG
Important Project of Common European Interest	IPCEI
Intergovernmental Panel on Climate Change	IPCC
International Energy Agency	IEA
International Renewable Energy Agency	IRENA
Joint Research Centre	JRC
Joint Undertaking	JU
Key Performance Indicator	KPI
Levelized cost of hydrogen	LCOH
levelized cost of hydrogen	LCOH2
Life-cycle assessment	LCA
Liquid organic hydrogen carriers	LOHCs
Megawatt	MW
Methane	CH4
Net-Zero Industry Act	NZIA
Nitrous oxide	N2O
Operational Expenditure	OPEX
Proton Exchange Membrane	PEM
Renewable Energy Directive	RED
Renewable energy sources	RES
Renewable fuels on non-biological origin	RFNBO
Strategic Research and Innovation Agenda	SRIA
Sustainable Development Goals	SDGs
United States	US

Summary

Summary

Scope of the Activity

The European Hydrogen Sustainability and Circularity Panel (EHS&CP)[1] was set up by the Clean Hydrogen Joint Undertaking (JU) in February 2024. Its mission is to facilitate the integration of sustainability and circularity principles into the JU's research projects and programmes. Comprising of 15 high-level European hydrogen experts, the EHS&CP provides advisory support both on the project and the programme level. The Panel also helps to disseminate knowledge to promote a culture of sustainability and circularity within the European hydrogen economy.

The Panel's work is organised into four task forces, allowing for in-depth research to be carried out in the following domains of the hydrogen value chain:

- hydrogen production
- hydrogen storage and distribution
- hydrogen end use
- cross-cutting issues.

This report presents the initial findings of the EHS&CP and comprises the fundamental issues of hydrogen research regarding the:

- current state of sustainability and circularity policies relevant to hydrogen
- potential impacts of scaling up hydrogen technologies
- circularity and sustainability indicators.

Methodology

Sustainability and circularity policies relevant to hydrogen

The Panel carried out a review of recent EU policies related to hydrogen to map the current landscape of sustainability and circularity considerations. The aim of the analysis is to develop indicators, definitions and measures to ensure hydrogen initiatives have a positive sustainability and circularity impact across all segments of the hydrogen value chain from production, distribution and storage to end-use and cross-cutting issues.

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[1] https://www.clean-hydrogen.europa.eu/get-involved/european-hydrogen-sustainability-and-circularity-panel/panel_en

Potential impact of scaling up the hydrogen technologies

The Panel analysed the impacts of scaling up hydrogen technologies, examining potential barriers and opportunities. Key aspects included:

- impacts on:
    - critical raw materials
    - water resources
    - land use
    - power systems
    - hydrogen storage and distribution
    - education
    - social acceptance
    - cooperation & stakeholder initiatives
- modelling needs for policy support.

Circularity and sustainability indicators

An exhaustive review of existing indicators was carried out. Each Task Force analysed and prioritised indicators based on the specific stages of the hydrogen value chain, emphasising a holistic perspective through a life-cycle approach.

The Panel shortlisted a series of indicators that were found as most adequate for monitoring progress across the sustainability dimensions, including criticality of raw materials, economic and social aspects, and circularity.

Such indicators were proposed for each dimension, together with their applicability and potential limitations. For example, recycling (and circularity) within the hydrogen sector was found to present challenges regarding the availability of benchmarking information for project evaluation purposes. A similar challenge was observed for social indicators.

Findings

Sustainability and circularity policies

Key issues identified:

- The analysis of the European and third-country policies found out that the EU sets ambitious targets for renewable hydrogen, while the US and Japanese policies are more open to other hydrogen types.

Impacts of scaling-up the hydrogen technologies

The Panel highlighted:

- The availability of critical raw materials may pose a challenge for scaling up renewable hydrogen production and hydrogen storage infrastructure
- The need to include factors such as air quality, eutrophication and biodiversity, in addition to cost and Greenhouse Gas (GHG) emissions, to comprehensively assess the benefits of large-scale hydrogen deployment
- The importance of considering multiple sustainability criteria (i.e. including social aspects, land use and water resources) and using multi-objective optimisation models to find the best trade-off solutions.

Indicators for sustainability hotspots

The report proposes a set of indicators to identify sustainability hotspots within the hydrogen value chain:

- Environmental impacts can be assessed using indicators from the Environmental Footprint methodology of the JRC
- Materials criticality is measured by the relative contents of critical and strategic materials with additional indicators for material supply risk
- Economic indicators include capital expenditure (CAPEX), operational expenditure (OPEX) and levelized cost of hydrogen (LCOH) which are widely used in the hydrogen sector
- Social indicators, particularly metrics related to job creation, are being developed.

Acknowledging the nascent stage of end-of-life strategies in the hydrogen sector, the Panel proposes indicators focusing on recyclable and recycled material content and by-product utilisation. While these indicators can be obtained from the JU projects, benchmarking information may be limited.

The current state of sustainability and circularity policies relevant to hydrogen

Introduction

The EU aims to achieve climate-neutrality by 2050[2], positioning hydrogen as a crucial element for meeting this objective as well as Europe's electricity and power generation needs. Hydrogen as an energy vector is pivotal for reducing hazardous emissions in industrial sectors such as chemicals production, long-haul transportation, steel production etc., where significant emission reductions are challenging and direct electrification is not possible.

The EU is a world leader in promoting sustainable hydrogen. Its Hydrogen Strategy[3] focuses on "renewable hydrogen" produced through water electrolysis using renewable energy, biogas reforming, or biomass conversion (if sustainable). The strategy also includes "low-carbon hydrogen," derived from nuclear or fossil sources with carbon capture, as a short to medium-term solution for emission reduction. Various organisations use colour labels to distinguish between hydrogen sources and conversion processes (Figure 1a).

By 2030, the EU aims to install at least 40 GW of renewable hydrogen electrolysers and produce up to 10 million tonnes of renewable hydrogen within the EU. An additional 10 million tonnes is expected to be imported from third countries[4]. To further reduce GHG emissions, the EU plans to upgrade current fossil-based hydrogen production processes with carbon capture technologies as a transitional solution until renewable hydrogen technologies become mature and widely deployed, particularly in hard-to-decarbonise industrial sectors. Thus, hydrogen is expected to be an essential element of the energy transition, offering substantial environmental, economic, and energy security benefits.

To achieve climate neutrality through hydrogen technologies, hydrogen production must quickly transition to renewable, carbon-neutral methods, as the majority of current production relies on fossil fuel methods (Figure 1b). Additionally, hydrogen production must scale up significantly to meet the expected soaring demand. In 2022, **global** hydrogen production totalled 95 million tonnes, generated predominantly from fossil fuels. Steam methane reforming of natural gas and coal gasification represented 83% of global hydrogen production with by-production at 16%. Global hydrogen production with carbon capture and use represented 0.6% and electrolytic hydrogen 0.1% according to the “Global Hydrogen Review 2023” published by the International Energy Agency (IEA)[5]. **In Europe**, electrolytic hydrogen accounts for 4% of production, as reported by the European Hydrogen Observatory (Figure 1b).

Encouragingly, international investments in hydrogen generation are projected to grow from 3.2 GW to 8.2 GW by 2030 (57% of that occurring in Europe). However, substantial efforts are

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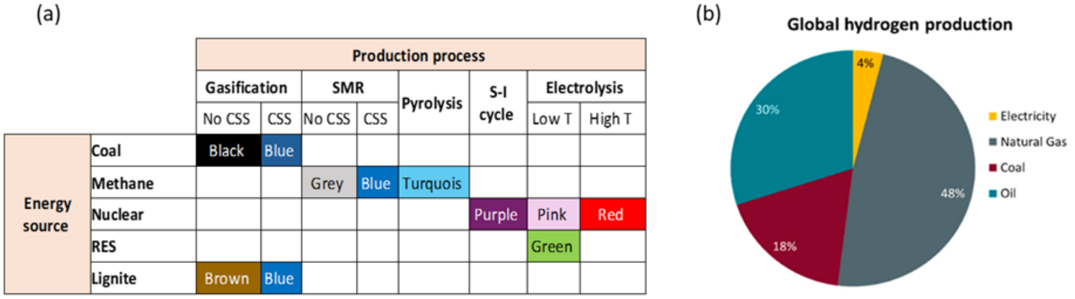
[2] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
[3] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final
[4] REPowerEU. Affordable, secure and sustainable energy for Europe, SWD(2022) 230 final.
[5] Global Hydrogen Review 2023 – Analysis - IEA

required to achieve the target of hydrogen contributing 13–14% to the European energy mix up by 2050[6].

Figure 1 a) Summary of typical classification of hydrogen color by energy source and process[7]. 1 b) Share of primary energy sources used for global hydrogen production in 2020 (adapted from Jaradat et al 2022[8]).


(a)

		Production process							
		Gasification		SMR		Pyrolysis	S-I cycle	Electrolysis	
		No CSS	CSS	No CSS	CSS			Low T	High T
Energy source	Coal	Black	Blue						
	Methane			Grey	Blue	Turquois			
	Nuclear						Purple	Pink	Red
	RES							Green	
	Lignite	Brown	Blue						

(b)

Establishing a hydrogen market in Europe will require the development, implementation, and management of completely new supply chains. These supply chains must ensure not only the production of massive quantities of hydrogen, but also its efficient, cost-competitive, and sustainable transportation, storage, and distribution.

Moreover, the difficulty of accessing low-carbon hydrogen at a competitive price in several countries could lead to the relocation of hydrogen production to countries with high renewable electricity potential such as Nordic countries, Spain, Portugal and even countries outside the EU (e.g. Marocco, Tunisia). This potential shift in production locations is being studied by the European Hydrogen Backbone initiative[9], which is working on defining the key infrastructural elements of a competitive and cohesive EU hydrogen network.

Forthcoming chapters of this report include:

- review of current EU policies that define the sustainability and circularity aspects of hydrogen,
- robust analysis of possible effects of scaling up hydrogen technologies,
- review of circularity and sustainability indicators needed to monitor potential effects of the energy transition.

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[6] https://commission.europa.eu/news/focus-renewable-hydrogen-decarbonise-eus-energy-system-2022-11-15-0_en.
[7] Based on descriptions by Hydrogen Europe in “The Colours of Hydrogen”;
[8] Jaradat, M.; Alsotary, O.; Juaidi, A.; Albatayneh, A.; Alzoubi, A.; Gorjian, S. Potential of Producing Green Hydrogen in Jordan. Energies 2022, 15, 9039. https://doi.org/10.3390/en15239039
[9] https://ehb.eu/

Current policies and their relation to the sustainability and circularity of hydrogen

EU policies, regulations, and strategies play a significant role in shaping the framework of sustainable and circular hydrogen. By now, 20 European countries and 43 countries globally have adopted national hydrogen strategy/policy documents, underscoring the global momentum towards prioritizing renewable hydrogen solutions.

In April 2024, the European Hydrogen Observatory[10] published a report[11] reflecting on the status of European and national policies, legislations, strategies, codes & standards impacting the deployment of hydrogen technologies and infrastructures. Taking into consideration the findings of that report as well as other relevant sources, this chapter provides a focused assessment of sustainability and circularity policies relevant for the EU hydrogen economy.

Key Policy Frameworks

European Green Deal & REPowerEU

The **European Green Deal** outlines the EU's commitment to becoming climate-neutral by 2050. It emphasises the importance of renewable energy and clean hydrogen in decarbonising various sectors, including industry, transportation, and heating. The Intergovernmental Panel on Climate Change (IPCC) estimates that to limit temperature increase to 1.5 °C by the end of the century, net-zero CO_2 emissions globally need to be achieved by around 2050, with neutrality for all other greenhouse gases following somewhat later.

Adopted by the European Commission in July 2021, **Fit-for-55** is a package of proposals designed to make the EU's climate, energy, land use, transport and taxation policies align with the target of reducing emissions by 55% by 2030. It is a broad package, containing 13 different proposals approaching emission reductions from different angles.

REPowerEU responds to the energy market disruptions caused by the Russian invasion of Ukraine and seeks to rapidly reduce the EU's dependence on Russian fossil fuels. It aims to complement and accelerate several ongoing EU legislative initiatives, first and foremost the Fit-for-55 package.

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[10] https://www.clean-hydrogen.europa.eu/knowledge-management/european-hydrogen-observatory_en

[11] European Hydrogen Observatory, 2024: The European hydrogen policy landscape https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-04/Report%2002%20-%20The%20European%20hydrogen%20policy%20landscape.pdf

Energy policies and strategies with a focus on hydrogen

EU Hydrogen Strategy

The EU Hydrogen Strategy, released in 2020, sets out a comprehensive roadmap for developing a hydrogen economy in Europe. It focuses on scaling up renewable hydrogen production, fostering demand across different sectors, and establishing a regulatory framework to support the deployment of hydrogen technologies. While it does not explicitly mention sustainability and circularity, these aspects are integral to the strategy's long-term goals.

Hydrogen Accelerator

The Commission dedicated an entire section of REPowerEU to hydrogen, setting an indicative, non-binding target of 10 million tonnes of domestic hydrogen production and 10 million tonnes of imported renewable hydrogen by 2030.

Renewable Energy Directive (RED II)

RED II sets binding renewable energy targets for EU Member States and includes provisions for promoting renewable hydrogen production. It also establishes sustainability criteria for biofuels, biogas, and biomass, ensuring that renewable hydrogen production aligns with environmental and social sustainability principles.

Delegated Acts

REDII stipulates the publication of two delegated acts, which were formally adopted in June 2023. These acts ensure that hydrogen is produced from renewable sources and achieves at least 70% emissions savings. Renewable hydrogen, hydrogen-based fuels or other energy carriers are defined as Renewable Fuels of Non-Biological Origin (RFNBO) and must be produced with renewable electricity.

The first delegated act introduces the concepts of additionality, temporal correlation, and geographical correlation. Additionality it ensures that the supply of renewable hydrogen is connected to new renewable energy sources. Temporal correlation requires RFNBO production to occur within the same calendar month (until 1 January 2030), and after this date, within the same one-hour period as electricity production from the contracted renewable energy sources (RES). Geographical correlation states that RFNBO and RES facilities must be located within the same or in an interconnected electricity market bidding zone.

The second delegated act establishes a minimum threshold for GHG emissions savings of recycled carbon fuels and specifies the methodology to calculate the GHG savings from renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels. Total emissions must include emissions from elastic inputs, rigid inputs, inputs of existing use or fate, processing, transport and distribution, and combustion of the fuel in its end-use, subtracting emission savings from carbon capture and geological storage where applicable. It sets a fossil comparator at 94 gCO_2/MJ; the 70% minimum reduction means that emissions must not be higher than 28.2 gCO_2/MJ. For hydrogen, this would mean 3.38 kg CO_2/kg H_2.

Renewable Energy Directive (RED III)

The revised Renewable Energy Directive (RED III) was published in the EU Official Journal on 31 October 2023 (Directive 2023/2413) and entered into force on 20 November 2023. RED III increases ambitions from 32% to a binding 42.5% of energy consumption in 2030, striving for 45%, which means roughly doubling the expansion of renewables (about 22% in 2021). RED III also creates a market ramp-up for e-fuels (RFNBO). In transport, it targets a 29% renewable fuel supply by 2030, with binding sub-targets of 5.5% for advanced biofuels and RFNBO. In buildings, the indicative renewable target is set at 49%. For the industry, the directive sets an indicative target of a 1.6% annual increase to 2030, and aims for 42% of hydrogen use from RFNBOs by 2030 and 60% by 2035. Table 1 depicts the main changes between RED II and RED III directives.

Table 1 RED II versus RED III – key changes

RED II	RED III
Share of energy from renewable sources - 32%.	The share of energy from renewable sources is 42.5% (with the intention of increasing the rate to 45%) by 2030.
Use of renewable or low-emission fuels in land transport.	Sustainability criteria used for areas intended for agricultural biomass production (excluded areas indicated).
Land, air and sea transport (use of renewable or low-emission fuels in air and sea transport).	Sustainability criteria also applied to forest biomass (considering the exclusion of peat bogs, primary forests with a high biodiversity status).
Sustainability criteria and GHG emission reduction for installations producing heat, electricity and cooling with a thermal power of at least 20 MW.	Sustainability criteria and GHG emission reduction for installations producing heat, electricity and cooling with a thermal power of at least 5 MW.
Sustainable development criteria for gaseous biomass fuels in installations producing electricity, heat and cold with a total nominal thermal power of at least 2MW.	Sustainability criteria for gaseous biomass fuels - in installations producing electricity, heat and cold with a total rated thermal power of at least 2MW and gaseous biomass fuels with a concentration exceeding 200 m^3 of methane equivalent/h.

Funding Mechanisms

The EU provides funding through various programs to support research, innovation, and demonstration projects aimed at advancing hydrogen technologies and accelerating their commercialization. These programs include:

- Horizon Europe,
- Innovation Fund,
- Connecting Europe Facility,
- Modernisation Fund,
- European Regional Development Fund,

- Cohesion Fund,
- React-EU,
- LIFE and the
- European Innovation Council.

Establishing a robust and globally competitive hydrogen economy is a strategic priority for the EU. This priority qualifies for financing under the Important Project of Common European Interest (IPCEI) umbrella. IPCEI projects must demonstrate overriding benefits for multiple EU Member States and show that the project would not be realised using private investment alone. There are currently four hydrogen projects under IPCEI with an overall value of over €17 billion[12].

Additionally, the EU has launched the Hydrogen Bank, which held its first auction for domestic hydrogen production in November 2023, further supporting the development of the EU's hydrogen economy.

Sustainability and Circularity Measures

Circular Economy Action Plan

The EU Circular Economy Action Plan promotes resource efficiency, waste reduction, and circularity across various sectors, emphasising the use of renewable energy sources. By integrating renewable hydrogen production and utilisation into circular economy principles, the EU aims to minimise waste generation, optimise resource use, and enhance the sustainability of the hydrogen value chain.

Carbon Pricing Mechanisms

The EU Emissions Trading System (ETS) and the proposed Carbon Border Adjustment Mechanism (CBAM) are pivotal carbon pricing methods. These instruments incentivise industries to reduce carbon emissions by internalising the cost of carbon, thereby encouraging investment in low-carbon alternatives such as renewable hydrogen. By fostering demand for sustainable and circular hydrogen solution, these mechanisms contribute to achieving EU climate goals.

Eco-design Directive

From the start of the 21st century, the European Commission has recognised eco-design as a powerful tool to support its ambition of becoming the first CO_2-neutral and circular economy in the world. On 18 June 2003, the Commission adopted its Communication on "Integrated Product Policy – building on Environmental Lifecycle Thinking", emphasising eco-design as a critical factor. Two years later the first eco-design directive was approved, initially focusing on energy-using products. In 2009, it was amended to include energy-related products, which are defined

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[12] Information from IPCEI Hydrogen https://ipcei-hydrogen.eu/

as "any good that has an impact on energy consumption during use which is placed on the market and/or put into service".

The Directive will be repealed in 2024 and replaced by the **Eco-design for Sustainable Products Regulation**. The available draft of this new regulation is more ambitious as it seeks to extend its scope to cover all products placed on the EU market, domestically produced or imported. This new regulation will introduce requirements for specific product groups, and will seek to improve the following aspects:

- product durability, reusability, upgradability and reparability,
- possibilities for refurbishment and maintenance.

Several other aspects will also be addressed including the presence of hazardous chemicals in products, energy and resource efficiency, waste generation and recyclability.

Green Claims Directive

Adopted by the European Parliament in April 2024, the Directive requires companies to substantiate the voluntary environmental claims they make in relation to their products and services. The Directive introduces requirements for businesses to back up their green claims with independent, peer-reviewed, widely recognised, robust and verifiable scientific evidence. The aim of the legislation is to provide more transparency for consumers and reduce greenwashing practices.

Legislation assessing hydrogen scaling up

Several legislative measures focusing on hydrogen scaling-up have been introduced, including the Critical Raw Materials Act (2024), the Alternative Fuels Infrastructure Regulation (AFIR)[13], FuelEU Maritime and ReFuelEU Aviation.

Of particular significance is the **Net-Zero Industry Act** (2024), which designates hydrogen technologies (i.e., electrolysers and fuel cells), as crucial technologies for decarbonising European industry and reaching the EU's climate targets by 2030 and climate neutrality by 2050. The Commission has also proposed that 40% of electrolysers and fuel cells used in the EU should be of European origin (this version of the text is not definitive and is subject to change).

Supporting Legislation and Initiatives

Hydrogen and Gas Markets Decarbonisation Package

On 21 May 2024, the EU Council adopted the Hydrogen and Decarbonized Gas Market Package, aiming to ensure the internal gas market functions while promoting renewable and low-carbon gases, including hydrogen. This regulatory framework supports hydrogen infrastructure development, cross-border trade, and the reuse of existing natural gas facilities

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[13] refers to targets for the deployment of hydrogen refuelling stations

for hydrogen projects. Once adopted, this package aims to provide the legal certainty necessary to drive investments into hydrogen infrastructure. Key provisions:

- **Networks**: Establishes common rules for hydrogen transport, supply, and storage, addressing market design and regulatory principles like unbundling and third-party access. It proposes the creation of the European Network for Network Operators of Hydrogen (ENNOH) to oversee network codes and development plans.
- **Markets:** Defines terms such as “low-carbon fuels,” “low-carbon hydrogen,” and “low-carbon gases,” with a stringent 70% greenhouse gas (GHG) reduction threshold for low-carbon hydrogen, equating to 3.38 kg CO_2/kg H_2. The regulation also sets a 5% hydrogen blending limit into natural gas at interconnection points.
- **Consumers:** Includes consumer protection provisions, such as faster switching of providers, access to comparison tools, billing information, and smart meters for natural gas and hydrogen.

Partnerships[14]

Under the Horizon Europe framework program for research and innovation, launched in 2021 with a budget of €95.5 billion, new forms of partnerships are established, including the Clean Hydrogen Partnership. This initiative aims to accelerate the development and improvement of advanced clean hydrogen technologies through collaboration between the public and private sectors.

International policies

Hydrogen is expected to become a globally traded energy vector, particularly between Europe and economies such as Australia, Chile, Morocco which have the potential to produce cheap renewable electricity. Therefore, it is necessary to understand how other major countries are defining clean or renewable hydrogen:

- Japan began research and development in the field of hydrogen as early as 1973 and formulated a hydrogen strategy in 2017. Hydrogen is one of the focal points of the strategy for green growth.
- The United States introduced a National Clean Hydrogen Strategy in June 2023 focusing on strategic applications in industry, transportation, and power sectors. Key principles include deep decarbonisation, innovation, domestic manufacturing, and affordability[15].

Unlike the EU, the US and Japanese strategies use a broader definition for “clean hydrogen” and describe it as hydrogen produced with low carbon intensity. The US aims to produce

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[14] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/european-partnerships-horizon-europe_en

[15] reducing the cost of clean hydrogen: 1$/kg of production cost by 2031, 9$/kWh of onboard storage cost at 700 bar, 2$/kg of delivery and dispensing cost

hydrogen with 2 kg or less of carbon dioxide (CO_2) equivalent emissions per kg of hydrogen. As part of the Inflation Reduction Act of 2023, a 60 cent tax credit is proposed for hydrogen that starts at 4 kg of CO_2 equivalent per kg of hydrogen. For hydrogen with less than 0.45 kg of CO_2 equivalent per kg, a maximum tax credit of $3 per kg is proposed.

While the EU demands hourly matching of renewable power to electrolyser operation after 2030, the US has set hourly matching from 2028 onwards. The US is also to enforce additionality to ensure clean energy is used for hydrogen production. The US Department of Energy (DOE) is funding the development of metrics and criteria to evaluate the impacts of hydrogen deployment on sustainability, such as water consumption, labour opportunities, air quality improvements and more. Circularity is not mentioned in the proposed text.

In contrast to the EU, where the focus is on renewable hydrogen from renewable electricity, the US strategy is broader focusing on all types of hydrogen production. Nonetheless, it offers the highest incentives for hydrogen produced with close to zero emissions. In this context, it is important to note that the US government was criticised last year by environmental groups after the announcement that four out of seven hydrogen hubs, which were to receive $7 billion from government funding, were producing hydrogen from natural gas via carbon capture and storage (also known as blue hydrogen).

Panel's recommendation

Following the review of relevant policy instruments, the Panel finds it critically important to:

- prioritise the development of sustainability and circularity approaches through robust regulatory frameworks,
- establish clear methodologies to accurately measure greenhouse gas emissions and environmental impacts of hydrogen throughout its entire lifecycle (cradle-to-grave approach).

Furthermore, based on the relevant analysis (see Annex II), current hydrogen certification and standards for sustainability and circularity should be reviewed as they were found to be unclear, complex, or still under development. This poses significant challenges for project developers.

The impact of scaling up hydrogen adoption

The impact of scaling up hydrogen adoption

The large-scale adoption of hydrogen-related technologies in the economy can have significant impacts and barriers. This section explores these aspects identifying potential impacts and key barriers. It also proposes enabling or mitigation measures aimed at enhancing the contribution of hydrogen to the transition towards sustainable energy system.

This chapter is divided into the following sections detailing the advantages and drawbacks of each area:

- Critical raw materials
- Impact on water resources
- Land use
- Impacts on the power sector: renewable energy for hydrogen production
- Hydrogen storage and distribution
- Education
- Acceptance and “Not In My Back Yard”
- Cooperation & stakeholders initiatives
- Modelling needs for policy support

Critical raw materials

Critical raw materials (CRM) are materials, metals or minerals which are of high economic importance for Europe while being also highly vulnerable to supply disruptions. Hydrogen and fuel cell technologies make use of some these critical raw materials. Additionally, in the context of energy transition, these CRMs are essential for the large-scale deployment of technologies that rely on intermittent renewable energy sources like wind and solar.

A recent World Bank study[16] highlights that primary raw material demand to produce clean hydrogen is expected to come from renewable electricity, rather than from the hydrogen technologies themselves. This demand primarily includes aluminium, copper, nickel, and zinc, with specific requirements depending on the type of renewable electricity used. For instance, solar photovoltaics is expected to drive aluminium demand, while wind energy might increase the need for zinc, dysprosium, and neodymium for turbines with permanent magnets.

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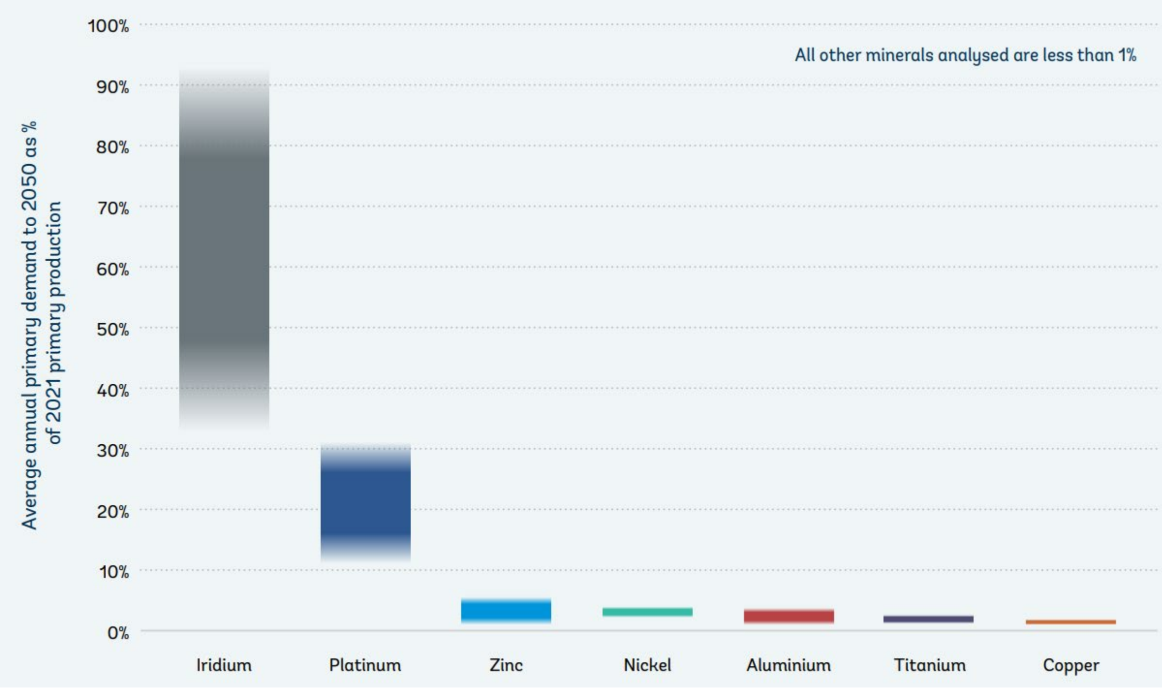
[16] https://documents1.worldbank.org/curated/en/099340012132232793/pdf/P1740030a03d520a60a5570f776c34e1701.pdf

Figure 2 Modelled average annual primary demand from renewable hydrogen production and consumption to 2050 as a percentage of current primary production[17]



Although the demand for CRMs for clean hydrogen production is relatively small compared to current production levels (see for example Figure 3, where the expected CRM demand in 2050 for hydrogen production is compared to the current production), it poses challenges due to potential shortages or price hikes, especially considering their broader use in the low-carbon transition. While the overall scale of material demand for clean hydrogen production isn't likely to pose significant market challenges, **certain materials such as platinum and iridium may face short-term supply constraints.**

According to the above-mentioned World Bank study, the demand for primary platinum from hydrogen production could surpass current total production levels by the 2030s, while iridium demand could exceed current total production by over 160% in the 2040s. Meeting this demand may be challenging due to production concentration and the nature of these materials as by-products. Strategies such as recycling, circularity, and material substitution are essential for

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[17] https://documents1.worldbank.org/curated/en/099340012132232793/pdf/P1740030a03d520a60a5570f776c34e1701.pdf

policymakers and the private sector to overcome these challenges and ensure a sustainable supply chain for clean hydrogen production.

Panel's recommendation

To enable large-scale deployment of hydrogen-based technologies, research and development must prioritise material optimisation for sustainability. In the case of alkaline electrolyser technology, this means transitioning to designs free of platinum and cobalt. While some manufacturers have already achieved this, others still rely on these materials, potentially limiting the future role of alkaline electrolysers.

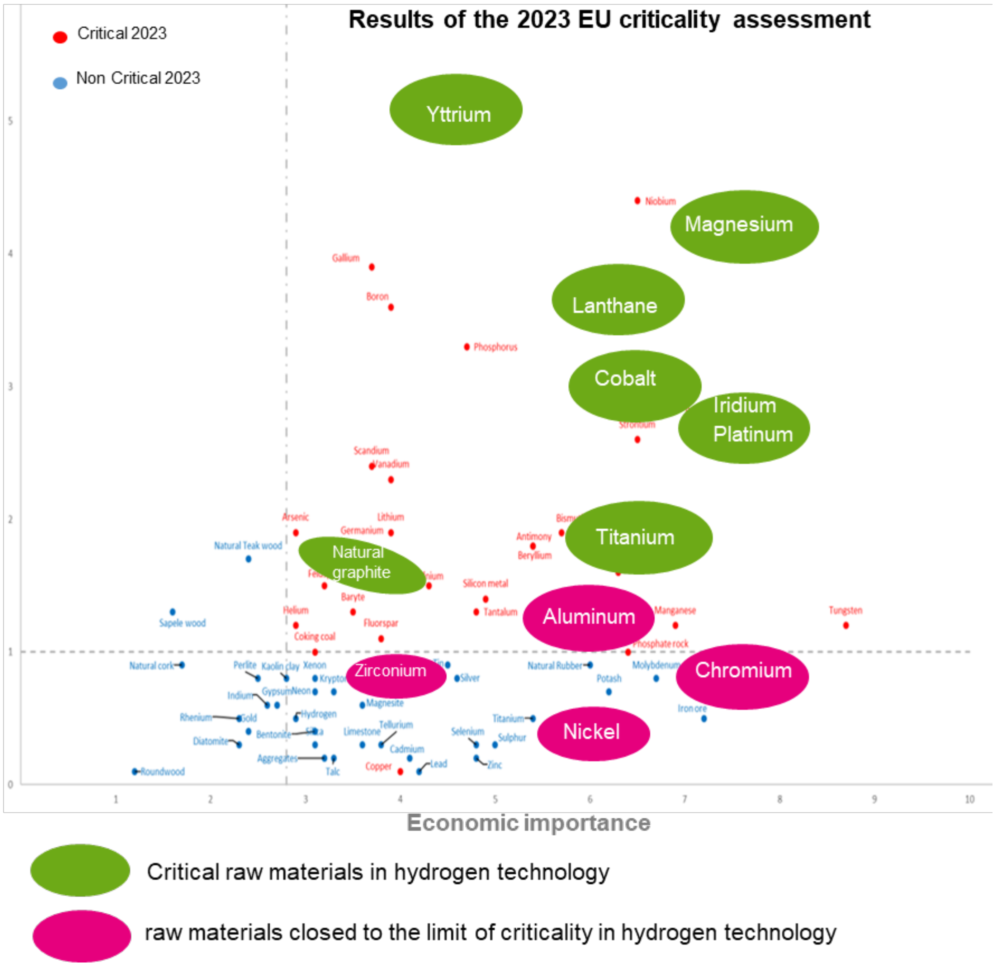
In the case of PEMEL, significant reductions of up to 70% and 80% in iridium and platinum content per unit of installed capacity, respectively, can be achieved. This reduction is made possible through a combination of research, increased hydrogen production through improved efficiency, and effective recycling strategies. This reduction is particularly crucial for iridium, which is predominantly sourced from South Africa and has a relatively small market size, which currently supports only about 75 GW of electrolysis capacity.

It is worth noting that high-temperature solid oxide electrolysis also involves CRMs, typically light and heavy rare earth elements, in small quantities which helps mitigate the high supply risk for these materials. The critical raw materials essential for hydrogen technologies are illustrated in Figure 4.

The upscaling of hydrogen storage and distribution infrastructure may also depend on the availability of several CRMs. The physical storage of hydrogen, whether in compressed or liquefied form, does not raise concerns regarding the utilization of CRMs, however its storage in certain chemical agents can pose challenges. Considering the volumes of hydrogen that will be transported and bonded in chemical compounds, ammonia (NH_3) will certainly play a major role in the decades to come. Nowadays, ammonia is produced through the Haber-Bosch process utilizing nitrogen and hydrogen at temperatures between 300°C and 500°C in the presence of a catalyst based on iron. Thus, the upscaling of storages of hydrogen in the form of NH_3 does not present any risk of enhancing the consumption of CRMs. The possibility of storing hydrogen in liquid organic hydrogen carriers (LOHCs) however can cause challenges related to the utilization of CRMs as catalysts for hydrogen **absorption and desorption**.

These two processes can occur at acceptable operating conditions only in the presence of platinum metal group catalysts, and the fact that the catalysts must be changed every few tens of hydrogenation and dehydrogenation cycles worsens this scenario. Considering the potential for large-scale, widely used solid-state hydrogen storage systems, the use of CRMs will likely become a significant issue. Magnesium, titanium, and vanadium are all used as storage materials in readily available solid storage systems. Examples of these materials include Mg and Mg-based alloys, Ti-Fe-Mn alloys18, and Ti-Zr-Mn-V-Fe alloys (HYDRALLOY® C)19. Strategies targeted at substituting pure metal sources for the synthesis of the storage material with recycled industrial sources will be critical, given the significance that this type of storage will play in locations where the footprint of the storage systems is significant. In this context, the European Critical Materials Act is a key initiative to minimise the risks related to the CRM supply for hydrogen technologies.

Figure 3 Critical raw materials in hydrogen technologies according to the 2023 EU List[20]



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[18] https://www.gknhydrogen.com/

[19] www.gfe.com/02_produkte_loesungen/01_legierungen/PDB/HYDRALLOY-C_2019-929_-2005-169_2004-732-_V6.pdf

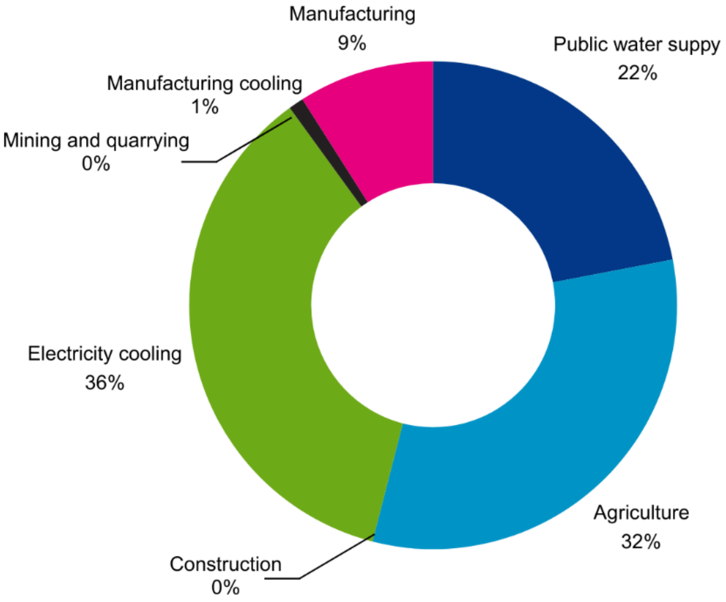
[20] Study on the Critical Raw Materials for the EU 2023 - Final Report - European Commission (europa.eu)

Impact on water resources

Clean hydrogen production requires significant amounts of water, the exact volume of which varies based on the technology employed and the water source utilised. For example, electrolysis can consume anywhere from 15 litres (using clean freshwater and air-cooling systems) to over 100 litres (using evaporative cooling and seawater) of water per kilogram of hydrogen produced, depending on the technology[21].

Water consumption of the hydrogen economy is often pointed out as a potential barrier to the large-scale deployment, and it is an important socio-economic and environmental impact. Hydrogen, however, is not the only industry relying on water as a resource. In Europe most of the surface- and groundwater is abstracted by the power sector.

Figure 4 Water abstraction from surface and groundwater resources in Europe in 2019[22]



According to IRENA, **hydrogen produced through water electrolysis** is the most **water-efficient** of all renewable and low-carbon hydrogen types. A recent study found that:

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[21] https://h2council.com.au/wp-content/uploads/2023/02/221114-Arup-Technical-paper-Water-for-Hydrogen-report-FINAL.pdf
[22] https://water.europa.eu/freshwater/countries/water-resources/european-union.

- Proton Exchange Membrane (PEM) electrolysis has the lowest water consumption intensity with an average water consumption intensity of about 17.5 litres per kilogram of hydrogen (l/kgH_2).
- Alkaline electrolysis is the second most water-efficient, with a water consumption intensity of approximately 22.3 litres per kilogram of hydrogen.

On the other end of the spectrum is fossil-based hydrogen, such as steam methane reforming–carbon capture, utilisation and storage (SMR-CCUS) or coal gasification with CCS. These technologies have the highest water consumption, with more than 30 litres per kilogram of hydrogen produced[23].

These distinctions highlight the importance of choosing electrolysis technologies, such as **PEM and alkaline electrolysis**, to minimize water consumption in the production of clean hydrogen.

In terms of the wider impacts of net-zero transition, a recent analysis from the International Energy Agency (IEA) found that the joint deployment of hydrogen, together with renewables such as wind and solar, could lead to a **decrease in water consumption from the energy sector** due to the lower amounts of water required for cooling in power plants running on fossil energy sources[24].

On the other hand, alternative energy sources may have a **detrimental impact both on water consumption and water quality**. For example, according to a recent study from the JRC, the impact of energy crops on water consumption could be significant, depending on the region. In some regions of France, for example, **water consumed for the irrigation of energy crops makes up over 90% of the overall water consumed** for energy production. In general, water use for energy crops is foreseen to increase and consistently account for a substantial share of the overall water consumption in the energy sector[25].

However, water scarcity is a local phenomenon. Therefore, the impact of hydrogen production on water reserves will have to be studied on a case-by-case basis. In drought-prone areas, the use of **desalinated seawater** may be recommended. Water desalination increases the energy requirement of hydrogen production, but this is negligible in comparison to powering the electrolyser itself. Overall, the reverse osmosis process used to produce desalinated water requires about 0.1 % of the minimum energy required to produce the hydrogen by electrolysis. From an economic viewpoint, the additional cost is limited, about $0.01 to the cost of hydrogen production per kg[26].

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[23] https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production.

[24] https://www.iea.org/commentaries/clean-energy-can-help-to-ease-the-water-crisis .

[25] https://publications.jrc.ec.europa.eu/repository/handle/JRC102696

[26] https://pubs.acs.org/doi/10.1021/acsenergylett.1c01375

Land use

The Fit-for-55 package explicitly aims to recognise the significance of forests and land use in attaining climate objectives. Expanding the implementation of hydrogen technology may encounter significant territorial limitations. Apart from the availability of water, the various facilities in the green hydrogen supply chains require the identification and allocation of suitable and sufficient land for the development of infrastructure. Potential sites can be found by using geospatial analytics and geographic information systems. Land use is a significant factor because green hydrogen requires renewable energy sources, and finding suitable sites for solar and wind power can be difficult due to both technological and geographical limitations.

However, it is worth noting that hydrogen production from non-dispatchable renewables, such as wind and solar, although requiring significant land for energy installations, may result in lower land use compared to biomass. Producing dedicated energy crops or forest biomass has a much larger land impact than wind and solar energy.

The construction of infrastructure such as depots, refuelling stations, and hydrogen production plants at certain demand points may be prohibited in some areas due to strict regulations and/or scarce land. Chen et al. (2022)[27] offer an illustration of the intricacy involved in integrating multiple tools to identify potential locations for a Japanese case study. The objective is to prioritise the construction of production facilities in accordance with policy regulations. This integration involves utilising extensive GPS trajectory records, geographical land use data, road network information, and Point of Interest (POI) data. In the EU the focus has so far been on mapping currently available infrastructure via initiatives such as the Hydrogen Infrastructure Map[28]. However, while there are studies looking into the spatial evolution of the hydrogen economy[29], there is a gap in identifying potential future locations, taking into consideration building restrictions as well as optimal supply chain connections.

Impacts on the power sector: renewable energy for hydrogen production

Developing of a robust green hydrogen economy requires a broad array of governmental actions and innovative strategies from industrial stakeholders. Currently, the cost of producing hydrogen from renewable sources exceeds that of hydrogen derived from fossil fuels. However, significant cost reductions can be realized through lowering the cost of renewable electricity and electrolysers, along with enhancing their efficiency and operational capacity.

As noted earlier, the EU delegated act CDR 2023/1184 sets forth guidelines for determining the eligibility criteria for electricity used in hydrogen production to be classified as fully renewable. This act clarifies the principle of "additionality" under the EU's Renewable Energy Directive, which mandates that electrolysers used for hydrogen production must be linked to new

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[27] Chen, J., Zhang, Q., Xu, N., Li, W., Yao, Y., Li, P., Yu, Q., Wen, C., Song, X., Shibasaki, R., & Zhang, H. (2022). Roadmap to hydrogen society of Tokyo: Locating priority of hydrogen facilities based on multiple big data fusion. Applied Energy, 313. https://doi.org/10.1016/j.apenergy.2022.118688

[28] https://www.h2inframap.eu/#introduction

[29] Wolf, André. (2023). The Spatial Evolution of a European Hydrogen Economy. Intereconomics. 58. 111-118. 10.2478/ie-2023-0022.

renewable electricity production, thereby promoting the expansion of renewable energy in the grid. Additionally, the act outlines methods to demonstrate compliance with additionality rules and introduces criteria to ensure that renewable hydrogen is produced only when there is sufficient renewable energy available.

As countries increase their renewable energy share, flexibility requirements will become more important. The variability and intermittency of renewable sources such as wind or solar pose challenges for maintaining a stable and reliable energy supply. Hydrogen can provide a solution to these challenges by acting as a flexible and efficient energy storage medium.

Hydrogen can be produced during periods of excess renewable energy generation and stored for later use. This stored hydrogen can be converted back into electricity or used in various applications when renewable energy generation is low. This capability helps to balance supply and demand, ensuring a continuous and stable energy supply, even when renewable sources are not generating power.

Therefore, hydrogen is vital for ensuring the long-term flexibility of power systems by mitigating seasonal variations in renewable production against electricity demand. Furthermore, storing hydrogen (or a hydrogen carrier such as methane, which already has extensive distribution and storage facilities) in large quantities can act as a strategic reserve with multiple applications, enhancing energy security and mitigating energy price volatility and crises.

Scaling up renewable hydrogen production will require substantial investment and expansion of electrical grids and hydrogen storage facilities. By 2050, electrolyser-based hydrogen production may consume nearly as much electricity as the global production today[30]. As more European sectors transition to electrification, a shortage of renewable electricity may impede green hydrogen production. Developing renewable hydrogen will demand a significant expansion of renewable capacity and electrolyser capacity on a gigawatt scale.

The approach to scaling up production will vary by region, as the levelized cost of renewables and, consequently, the price of hydrogen differs significantly. Renewable hydrogen production will be most economically viable in regions with abundant renewable resources, available land, access to water, and efficient energy transportation to major demand centres.

Although renewable costs are decreasing globally, significant disparities persist across countries and regions. Developing countries in tropical regions have a natural advantage in solar energy. Capital costs and the cost of capital can vary significantly across regions, resulting in substantial cost advantages for some countries. However, limitations exist in terms of land availability for deploying large-scale renewable-based electrolysis installations.

The primary impact on land will arise from the construction of extensive wind and solar PV farms needed to meet renewable electricity and green hydrogen demand. Regions with high renewable potential and low levelized electricity costs can become major green hydrogen

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[30] https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

producers. However, various technical, political and social aspects have to be considered such as existing infrastructure, government support, political stability, training and education to evaluate a country's capacity as a significant green hydrogen producer.

Hydrogen storage and distribution

There are three commonly used methods **to transport and distribute** pure hydrogen:

- (1) as a gas in specific pipeline networks,
- (2) in tube trailers as high-pressure gas, and
- (3) in tankers as cryogenic liquid.

Pipelines for hydrogen transportation are usually installed in areas where demand is high (hundreds of tonnes per day) mostly near industrial sites. Transporting significant amounts of hydrogen requires the construction of new pipelines, which will take time and considerable capital. However, it is difficult to attract sufficient investments for these developments in the absence of a stable hydrogen market. A potential solution could be the repurposing or reusing of current natural gas infrastructure. This could prevent these assets from going unused as economies transition from fossil to renewable energy sources and could also reduce the environmental impact of hydrogen infrastructure development.

Tube trailers, liquid tankers, and liquefaction plants are used in areas where demand is new or on a smaller scale. Larger scale demonstrations of hydrogen supply by chemical carriers such as ammonia, LOHC, metal hydrides, etc. are being developed. Pipeline transportation of gaseous hydrogen was found to have the least negative environmental effects when it comes to storage and transportation[31]. This is due to the fact that more electricity is required to liquefy hydrogen than compressing it, making liquid hydrogen transport more environmentally impactful. Rail-based hydrogen transportation is less burdensome than road-based hydrogen transportation. In comparison to trucks that run on diesel, it is expected that trains used for the distribution of hydrogen run on electricity and use less energy per transit distance. Even for short distances (e.g., 100 km), rail transport is a more environmentally friendly mode of hydrogen transportation. Since transportation is one of the main causes of GHG emissions, **future research should concentrate on identifying modes of mobility with reduced energy consumption and emissions**.

Regarding the possibility of **storing hydrogen** in chemical substances, there are risks to the environment if they are not produced, handled and transported appropriately. With an annual global manufacturing capacity of over 230 million tonnes (Mt), NH_3 is currently the second most manufactured chemical in the world[32]. Considering the quantities of hydrogen that Europe is planning to import from overseas countries and the state of development of the ammonia industry and the technology to utilize it as a hydrogen carrier, it is likely that NH_3 will play a major

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[31] Robert Hren, Annamaria Vujanović, Yee Van Fan, Jiří Jaromír Klemeš, Damjan Krajnc, Lidija Čuček, Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment, Renewable and Sustainable Energy Reviews, Volume 173, 2023, 113113,

[32] R. Hren et al., Renewable and Sustainable Energy Reviews 173 (2023) 113113.

role in overseas hydrogen transportation[33]. **Ammonia leaks** at various points during storage and transportation could have a variety of direct and indirect effects on the environment. Apart from the immediate detrimental impacts of NH_3 emissions on air quality, ammonia can exacerbate PM_{10} and $PM_{2.5}$ concentrations, particularly in big cities, by acting as a precursor to particulate matter (denoted as p-NH_4^+ and w-NH_4^+, respectively)[34]. Additionally, elevated NHx, *i.e.*, NH_3, p-NH_4^+ and w-NH_4^+, concentrations and deposition cause negative impacts on ecosystem structure and function (*e.g.*, biodiversity declines, soil acidification, water eutrophication) and significant economic loss.

The storage of hydrogen in metal hydrides can also pose serious concerns regarding its environmental impact. Although the amount of metals that are currently used for producing metal hydrides is neglectable, this will change once hydrogen replaces fossil fuels in many industrial sectors. At that point, the forecasted increase of **metal demand for hydrogen storage purposes**, e.g., magnesium, titanium, aluminium, iron, etc., **will raise concerns** over the exploitation of the Earth´s natural resources and over the environmental impact that the **extraction of metal** causes, *i.e.*, deforestation, erosion, contamination and alteration of soil profiles, streams and wetlands. Moreover, concentration, smelting, separation, and refining are required to produce metals in highly pure form as they are typically not mined as primary (virgin) metals but rather as ores. The mentioned processes are **energy-intensive** and often **rely on fossil fuels**, either directly as a reductant or indirectly for heat and electricity, thus leading to the release of large quantities of GHGs. In this scenario, metal recycling from materials or products that reached their end of life should be considered mandatory. This could save resources and energy while simultaneously prevent the depletion of natural resources and the reduce the release of harmful pollutants.

Even though some of the potential LOHC chemicals mentioned in the literature for hydrogen storage purposes are common organic compounds, there is a lack of information regarding their risks and impacts. Basic ecotoxicological parameters of these LOHC chemicals are missing alongside some basic information such as their solubility in water. Since the majority of proposed LOHC structures are organic, uncharged compounds, they will inevitably have an affinity for organic phases (such as organic matter, biological membranes, etc.), be somewhat volatile (with a technical tendency to use representatives of relatively low vapour pressure to allow easy hydrogen/LOHC separation), and have limited aqueous solubility[35]. Thus, given the **close affinity of these compounds to some of the most common fossil fuels** and their derivates, it is possible to assume that **their impact on the environment** (synthesis and accidental

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[33] Global Ammonia Industry Outlook to 2025 - Capacity and Capital Expenditure Forecasts with Details of All Active and Planned Plants; Global Data, February 2021.

[34] Negro, V.; Noussan, M.; Chiaramonti, D. The Potential Role of Ammonia for Hydrogen Storage and Transport: A Critical Review of Challenges and Opportunities. Energies 2023, 16, 6192.

[35] Shim, C.; Han, J.; Henze, D.K.; Shephard, M.W.; Zhu, L.; Moon, N.; Kharol, S.K.; Dammers, E.; Cady-Pereira, K. Impact of NH3 Emissions on Particulate Matter Pollution in South Korea: A Case Study of the Seoul Metropolitan Area. Atmosphere 2022, 13, 1227.

releases) **is similar**. However, it is important to keep in mind that while fossil fuels are burned, LOHC systems function as a sort of "deposit bottle" for hydrogen.

Additionally, the appropriateness of the hydrogen storage and distribution infrastructure will have to consider **minimising hydrogen leakages into the atmosphere** as there are increasing concerns related to the long-known atmospheric warming effects[36], which eventually would have significant consequences for a developing hydrogen economy.

Hydrogen can participate in atmospheric chemical reactions that affect the lifetime and atmospheric concentration of other greenhouse gases[37]. Therefore, **hydrogen could indirectly contribute to global warming.** Although the impact of hydrogen leakages is not yet fully understood, several research institutions and research projects, e.g. NHyRA[38], are investigating the potential atmospheric effects from hydrogen leaks as a result of a widespread hydrogen economy.

Large-scale seasonal energy storage can be achieved by storing hydrogen in **underground salt caverns and gas fields**, which are abundant across Europe. Subsurface geological formations such as aquifers, depleted hydrocarbon reservoirs, and salt or hard rock caverns provide the necessary large volumes, enhanced safety, low operational costs, and existing infrastructure for this purpose. However, these environments harbour diverse microbial communities that thrive under extreme conditions. Microbial activity can consume stored hydrogen, produce hazardous by-products like hydrogen sulphide (H_2S), form biofilms that lead to biological plugging, and induce corrosion, complicating storage efforts. Addressing these **microbial challenges** requires a thorough understanding of microbial metabolic processes, the development of effective mitigation strategies, and the advancement of predictive models to ensure the efficient and safe storage of hydrogen. Recent studies[39] highlight the significant impacts of microbial activity on hydrogen storage and emphasize the need for ongoing research to optimize these storage solutions. EU-funded projects, HyUSPRe[40] and Hystories[41] are currently investigating the feasibility and potential of implementing large-scale storage of renewable hydrogen in porous reservoirs in Europe.

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[36] Prather, M., Ehalt, D., & Kirchhoff, V. W. J. H. (2001). Atmospheric chemistry and greenhouse gases.

[37] Sandhiya L., Madhulika B., Unravelling the atmospheric and climate implications of hydrogen leakage.

[38] https://www.clean-hydrogen.europa.eu/projects-dashboard/projects-repository/nhyra_en

[39] Liu, X., Zhang, Y., Wang, Y., & Li, J. (2022). Hydrogen consumption by halophilic sulfate-reducing microorganisms in a pressurized microfluidic chip mimicking porous media structure. International Journal of Hydrogen Energy, 47(5), 2935-2948. DOI: 10.1016/j.ijhydene.2021.11.045
Schwab, V. F., Horth, A., & Weege, S. (2023). Microbial community response to varying salt concentration and carbon sources under hydrogen atmosphere in hypersaline gas storage sites. Applied and Environmental Microbiology, 89(3), e01542-22. DOI: 10.1128/AEM.01542-22
Tremosa, J., Pujol, M., & Ganot, S. (2023). Modeling microbial impacts on hydrogen storage: A comparison of three existing models based on field data.*Geochimica et Cosmochimica Acta, 317, 123-139. DOI: 10.1016/j.gca.2023.02.018

[40] https://www.hyuspre.eu

[41] https://hystories.eu/project-hystories/

Education

To achieve a sustainable circular economy on global scale, climate change problems and solutions must be recognised within our education system to drive a socio-economic transformation process. The EU's future sustainability and circular economy goals aim to transform linear production and consumption into a responsible circular economy. Schools, universities, and other educational institutions are essential for closing the gap in societal awareness on this issue and driving a global ecological transition. Education is the seed for building sustainable and circular futures. Therefore, broad-based educational initiatives must be part of scaling up and adopting hydrogen technologies. In addition, low-threshold information initiatives (e.g. advertising, social media) can enhance public knowledge about hydrogen, reduce unfounded fears and increase knowledge about its positive impacts on a future sustainable energy system. Energy transition will require informed, responsible and active citizens.

Acceptance and "Not In My Back Yard"[42]

Public acceptance of hydrogen technology can be influenced by various factors such as awareness, attitudes, perceptions, lifestyles, and preferences. Qualitative analyses using survey-based or interview methodologies combined with statistical analysis are the most common methods for investigating social acceptance of different hydrogen technologies.

Attitudes toward land use can impact the acceptability of hydrogen technologies as social opposition sometimes arises against the installation of hydrogen refuelling stations or production plants in close proximity to communities. These opposition is referred to as "Not In My Back Yard" (NIMBY) objections. According to Schönauer & Glanz (2021)[43], NIMBY is characterised by "a positive attitude towards the technology itself, but a lack of acceptance or even rejection of related infrastructure in one's neighbourhood, such as pipelines to transport hydrogen or hydrogen storage sites".

As per the survey reported in "Awareness of Hydrogen Technologies" (EC 2023[44]), the awareness of hydrogen is widespread, with more than eight out of ten respondents in the EU having recently seen, read, or heard something about it. Public perception of hydrogen products and technologies can be influenced if more information about hydrogen safety and sustainability implications is made available. This is highlighted by a specific objective outlined in the Clean Hydrogen Partnership Strategic Research and Innovation Agenda (SRIA)[45]: "Increase public and private awareness, acceptance, and uptake of clean hydrogen solutions, in particular through cooperation with other European partnerships under Horizon Europe."

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[42] Common acronym used for 'Not in My Back Yard'

[43] Schönauer, A. L., & Glanz, S. (2021). Hydrogen in future energy systems: Social acceptance of the technology and its large-scale infrastructure. International Journal of Hydrogen Energy. https://doi.org/10.1016/J.IJHYDENE.2021.05.160

[44] Awareness of Hydrogen Technologies - Survey Report - European Commission (europa.eu)

[45] 8a35a59b-a689-4887-a25a-6607757bbd43_en (europa.eu)

Public acceptability can be influenced by: (1) accessibility in terms of cost of hydrogen products/fuel, (2) infrastructure availability, (3) safety, (4) positive perception (e.g., environmental awareness, practicality, etc.).

However, investors may prioritise other aspects, such as: (1) market size, (2) regulatory framework, (3) subsidies, etc.

Cooperation & stakeholders initiatives

Stakeholders from industry, government, education, and research organisations have a crucial role in hydrogen scaling up efforts. Effective collaboration between these stakeholder groups is critical for expanding the hydrogen economy. However, coordinating a large number of actors across different countries and entities can pose challenges.

Stakeholders may have different visions, interests, priorities, and ambitions which can sometimes conflict and affect social interactions and levels of trust. Understanding the dynamics between these stakeholders - referred to as **agent dynamics** - helps capture diverse perspectives and conflicting interests. This understanding is essential for identifying common objectives and incentives that can enhance collaboration among stakeholders.

Modelling needs for policy support

Developing more comprehensive models and scenario analysis tools is fundamental to grasping the added value of large-scale adoption of hydrogen. The techno-economic optimisation models currently used to support the policymaking process have certain methodological limitations concerning some features which can be critical for the future deployment of hydrogen.

Future models of hydrogen supply chains or infrastructure must incorporate, for instance, sustainability requirements. **The outcomes of sustainable hydrogen models should align with global frameworks** such as the Sustainable Development Goals (SDGs) or Life Cycle and Sustainability Assessment to allow comparison with other energy supply chain alternatives. **Trade-offs** among the antagonist sustainability criteria, **such as cost and environmental impact**, **should be identified and analysed** before the selection of the best trade-off solution that integrates both sustainability and circularity. It is important not to rely solely on top-down approaches but to incorporate analyses that involve a combination of different scales, scenarios, and actors.

The most widely used scenario analysis models provide a comprehensive representation of GHG encompassing CO_2, CH_4, and N_2O. Some of these models also provide an approximate representation of local air pollutants such as $PM_{2.5}$, PM_{10}, NO_X, SO_2, NH_3, NMVOC, CO. However, the significance of hydrogen technologies extends beyond GHG emissions reduction and they also impact various other critical areas including **broader environmental, health, social, and geopolitical considerations.**

Reducing GHG emissions usually results in the reductions in air pollution. However, transitioning to low-carbon energy can take various technological pathways, each with its own a spectrum of potential health impacts pathways. **Hydrogen as an energy carrier, has broader environmental impacts beyond GHG emissions savings. The exact types of impacts depend on the energy sources used for hydrogen production.** These impacts include **air quality** (for example, in the EU, 40,000 premature deaths are caused by biomass combustion alone[46]), **eutrophication** (400 and more water systems worldwide are considered dead zones[47]), **loss of biodiversity** and **land use**, and other significant environmental considerations.

Moreover, the deployment of hydrogen technologies facilitates both the domestic production of renewables and the diversification of energy supply. Hydrogen deployment can enable a larger integration of non-dispatchable renewables by storing the excess power or using it for producing RFNBO. Additionally, it may allow the importation of energy in the form of low-cost hydrogen from countries with high renewable energy resources, reducing dependence on fossil fuel exporting countries.

Additionally, hydrogen technology contributes to positive socio-economic impacts, especially in terms of geopolitical stability. Much of the world's geopolitical instability is linked to or fuelled by fossil energy sources, which can lead to poverty and humanitarian crises. Therefore, it is crucial to investigate the implications of alternative European low-carbon pathways taking into consideration impacts beyond greenhouse gas emissions.

In addition to the limited number of currently available scenario analysis tools, the spatio-temporal resolution of long-term integrated energy system models also limits their ability to accurately simulate power system operations. The current models struggle to take into account short-term variations in the power system associated with the increasing penetration of variable renewable energy. They often oversimplify the ability of power systems to accommodate intermittent renewables.

Moreover, most energy system models are disconnected from power grid and natural gas grid models. While EU stakeholders such as ENTSO-G, ENTSO-E[48] and the JRC[49] have been assessing European grid infrastructure impacts of blending hydrogen into the energy mix, a **closer link between energy system models, unit commitment and economic dispatch models alongside energy network models, could improve the quantification of hydrogen technology's contribution** to integrating non-dispatchable renewable energy sources into energy systems, exemplified by power-to-gas technologies. This would lead to a **better understanding of the potentials** and benefits associated with the widespread adoption of hydrogen technologies at scale. Thus, there is a **need to develop suitable models with**

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[46] https://erj.ersjournals.com/content/erj/early/2015/09/24/13993003.01865-2014.full.pdf
[47] https://www.science.org/doi/abs/10.1126/science.1156401
[48] EMTSO-E, ENTSO-G Ten-Year Network Development Plans https://tyndp.entsoe.eu/explore/what-are-the-scenarios
[49] Joint Research Center, 2022 : Blending hydrogen from electrolysis into the European gas grid https://publications.jrc.ec.europa.eu/repository/bitstream/JRC126763/JRC126763_01.pdf

alternative optimization paradigms. These models should go beyond the conventional focus on minimizing the cost of the energy system while adhering to predefined GHG emission targets. Instead, they should incorporate a broader cost function encompassing health, environmental, and socioeconomic outcomes.

When multiple sustainability criteria are considered, multi-objective optimisation can be used to find the best trade-off solutions. As an example, cost, carbon emission, safety risk and other social criteria can be included in such analysis. CO_2 emissions reduction is a key driver in the development of hydrogen technologies. For this reason, the impact of CO_2 emissions - by considering the life-cycle assessment of different technologies - should always be analysed and compared with other energy alternatives. It is also possible to consider the effect of supply chain integration when carbon emissions from renewable sources, production type, storage, conditioning, transportation, and distribution are aggregated. This would allow the quantification of carbon emission for different capacity levels allowing the analysis to consider the impacts of scaling up. Additional efforts in scenario analysis are needed to account for relevant sustainability and circularity aspects such as water use, land use, critical materials, etc. A significant challenge lies in adapting these measures to different contexts. Moreover, some indicators such as safety risk index, critical materials use, efficiency, etc. must be analysed by using a long-term multi-period perspective due to changes in technological maturity. In terms of education and labour constraints, these are so far more difficult to quantify. The effects of policies and regulations can also be incorporated in scenario analysis for scaling up with an emphasis on how competition or cooperation between stakeholders can influence outcomes.

Co-funded by the European Union

Circularity and sustainability indicators for hydrogen

Circularity and sustainability indicators for hydrogen

Based on a comprehensive literature review assessing indicators within the hydrogen sector, a list of relevant indicators was compiled (Annex I).

As noted earlier, the EHS&CP experts carry out their work in four task forces that focus on specific elements of the hydrogen value chain, namely production, storage and distribution, end-use and cross-cutting issues. The four EHS&CP task forces assessed indicators according to their specific hydrogen value chain focus area. The set of indicators proposed in this section are selected to cover the dimensions of **sustainability** (including environmental, economic, and social aspects) as well as **materials criticality and circularity**.

Current sustainability challenges require, among others, the definition of systemic approaches to address the increasing complexity of systems. In this regard, the life-cycle perspective presents a complete map of the problem, facilitating the identification of opportunities for improving the performance of systems across entire value chains. In the specific case of hydrogen energy systems, when focusing on the environmental dimension, **LCA arises as a well-established methodology to quantify potential impacts**. Focusing on the European level, the Environmental Footprint is the reference LCA-based methodology for evaluating the environmental performance of products and services.

The social dimension is a relatively novel area, but its application to hydrogen energy systems is still limited. Indicators in the social area have been identified based on the “Guidelines for Social Life Cycle Assessment of Products”[50] by the UNEP/SETAC Life Cycle Initiative, which allows an evaluation from a value-chain perspective.

Another area, which has not yet been well developed for hydrogen systems is the assessment of the socio-economic and environmental impacts of the **End-of-Life (EoL) phase**. The main references for identifying indicators on circularity and criticality in the EoL phase come from European research projects[51] that specifically focused on this issue.

In the following sections, more details on the identification of the Key Performance Indicators (KPIs) for these dimensions are provided.

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[50] UNEP/SETAC Life Cycle Initiative. Guidelines for Social Life Cycle Assessment of Products. Social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development. Catherine Benoît and Bernard Mazijn, Editors. 2009. ISBN: 978-92-807-3021-0

[51] Petra Zapp, FZJ, Andrea Schreiber. D3.1 Material criticality indicator. SH2E Project. www.sh2e.eu

Environmental dimension

Environmental indicators are selected based on the recommendations from the EC Environmental Footprint impact categories[52]. The list summarised in Table 2 includes only the 16 main impact categories (sub-indicators are excluded), which are part of the current Environmental Footprint (EF) v3.1 Life Cycle Impact Assessment Method.

According to the latest review in 2023, the EF Impact Assessment Methodology periodically screens and recommends the list of relevant environmental indicators. This methodology is mentioned in the Green Claims Directive[53] as means to substantiate environmental claims for products and services. Considering potential future updates of the EF methodology is crucial within the scope of this document.

Although the list of indicators may appear extensive, the most challenging task in a life cycle assessment is the “inventory building” process, which requires these environmental indicators. For instance, the calculation of the carbon footprint of a production process requires the 16 categories proposed. This methodology is already integrated into the main LCA software (e.g., OpenLCA, SimaPro, GaBi), facilitating the provision of these indicators by LCA practitioners. It is important to estimate all these indicators to have the overall picture and to determine if burden shifts happen among environmental categories.

Table 2 Environmental indicators proposed in the Environmental Footprint v3.1 methodology

Impact category	Indicator	Unit	Characterization model
Climate change, total	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\ eq}$	Bern model - Global warming potential (GWP) over a 100-year time horizon based on IPCC 2021 (Forster et al., 2021).
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11$_{eq}$	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)
Particulate matter	Human health effects associated with exposure to PM2.5.	Disease incidences	PM model (Fantke et al., 2016 in UNEP 2016)

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[52] EU Commission Recommendation 2021/2279, Annex I, paragraph 3.2.3

[53] https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)753958

Impact category	Indicator	Unit	Characterization model
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model as developed by Dreicer et al. (1995) and published in Frischknecht et al. (2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg $NMVOC_{eq}$	LOTOS-EUROS model (Van Zelm et al., 2008) as applied in ReCiPe 2008
Acidification	Accumulated Exceedance (AE)	mol H^{+}_{eq}	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008.
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008
Ecotoxicity, freshwater*	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), adapted as in Saouter et al. (2018)
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA model (De Laurentiis et al. 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq. deprived water	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP 2016)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}	van Oers et al., 2002 as in CML 2002 method, v.4.8
Resource use, fossil	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	van Oers et al., 2002 as in CML 2002 method, v.4.8
Table taken from "Andreasi Bassi S., Biganzoli F., Ferrara N., Amadei A., Valente A., Sala S., Ardente F., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/798894, JRC130796". For further information, please, consult this reference			

Economic dimension

The levelized cost of hydrogen (LCOH2) or levelized cost of the final product or service is a commonly used economic indicator which evaluates the cost-effectiveness of hydrogen production systems.

The primary purpose of LCOH2 is to estimate the overall production cost of hydrogen, taking into account both initial investments and ongoing operational expenses over the system's lifetime (including loss in production and/or replacement). It serves primarily for comparative purposes and not as an absolute value, allowing stakeholders to assess the cost-efficiency and competitiveness of different hydrogen production methods against a standard or benchmark system. In the context of Strategic Research and Innovation Agendas (SRIA), the focus typically lies on the components that make up LCOH2 rather than the indicator itself. These components - CAPEX, OPEX, and degradation rate - are essential for detailed economic analysis and strategic planning within hydrogen-related initiatives.

Social dimension

The list of indicators in Annex I is based on the “Guidelines for Social Life Cycle Assessment of Products”[54] by the UNEP/SETAC Life Cycle Initiative. These indicators were categorised according to stakeholder groups. It is important to note that this methodology is still in its early stages and requires further development. One of its main challenges is the limited availability of information, despite the existence of commercial databases.

Currently, methodologies and factors for quantifying these indicators are provided in Commercial Social LCA databases (e.g., PSILCA, SHDB) which can be integrated into LCA software to facilitate their calculation. Several hydrogen focused studies have used social indicators such as forced labour, child labour, women's participation in the labour force, gender wage gap, and health expenditure, among others.

The above proposed indicators can be readily estimated for monitoring purposes at the project level[55] using or requesting data and statistics. However, it is essential to acknowledge that there is a scarcity of data at the level of various industries and this may pose challenges when benchmarking these indicators against competing technologies.

Materials Circularity

As the European hydrogen economy is evolving, it is important to note that end-of-life processes of hydrogen systems have not yet been developed at an industrial level. This means that specific processes for hydrogen systems’ recycling are yet to be explored. While some JU projects such as HyTechCycling and Best4Hy[56] proposed different strategies and processes up to TRL 5, there is still a lack of data and information, which makes it difficult to identify indicators for EoL processes.

In terms of circularity, the SRIA proposes three indicators related to recycling such as:

- minimum % of platinum (Pt) recycled from scraps and wastes,

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[54] UNEP/SETAC Life Cycle Initiative. Guidelines for Social Life Cycle Assessment of Products. Social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development. Catherine Benoît and Bernard Mazijn, Editors. 2009. ISBN: 978-92-807-3021-0

[55] Meaning individual hydrogen research or hydrogen development projects

[56] HyTechCycling: New technologies and strategies for fuel cells and hydrogen technologies in the phase of recycling and dismantling. DOI 10.3030/700190

Best4Hy: Sustainable solutions for recycling of end of life hydrogen technologies. DOI 10.3030/101007216

- minimum % of CRMs/ platinum group metals (PGMs) other than Pt recycled from scraps and wastes and
- minimum % of ionomer recycled from scraps and wastes.

The Panel has found that the above three indicators may not be sufficient to comprehensively assess the environmental impacts of end-of-life processes. Therefore, the panel recommends considering the usage of the following indicators:

- Recyclable materials content (%) – this includes the share of materials that could potentially be recycled due to the availability of relevant technology and the material composition.
- Recycled materials content (%) – this indicator identifies the share of material content actually recycled by the operator. Recyclability may be limited by access to technology, material quality and composition.
- By-product utilization (%) – this indicator describes the share of materials by-products or co-products that have been generated during hydrogen production and are reused, recycled, or valorised.

These indicators can be easily estimated at the project level but the available information to benchmark them is limited.

Materials criticality

In assessing materials criticality for hydrogen production, the following indicators are considered most suitable:

- Content of critical materials (%, g/kg H_2),
- Content of strategic materials (%, g/kg H_2).

These indicators could be combined by aggregating the amounts of critical and strategic materials used. They align closely with the indicators proposed in the SRIA for recycling. Calculating these indicators involves weighting the materials present in devices and systems according to the EU's 2023 list of critical and strategic materials.

Assessing the sustainability of raw material sourcing for hydrogen production can minimise the environmental impacts and ensure compliance with ethical standards. It is also vital for safeguarding transparency and traceability in the hydrogen supply chain to reduce the risk of environmental harm and unethical practices. Additionally, secondary indicators such as supply risk through the SR*EI (Supply Risk * Economic Importance) or the SH2E indicators[57] are relevant. These can be easily estimated from the information published by the European Commission[58].

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[57] Petra Zapp, FZJ, Andrea Schreiber. D3.1 Material criticality indicator. SH2E Project. www.sh2e.eu

[58] European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Ighilahriz, M., Update of the 2015 material system analyses – Final report, Publications Office of the European Union, 2024, https://data.europa.eu/doi/10.2873/440874

Summary of the proposed indicators

Drawing on the expertise of the Panel, Table 3 presents the indicators proposed for project/programme level monitoring. While environmental indicators benefit from a well-established methodology and CAPEX enjoys widespread usage, methodologies for calculating the remaining indicators must be developed to foster harmonisation and ensure fair comparison. Even for well-established indicators such as OPEX, clarity regarding the inclusion of maintenance costs is paramount, as variations in this aspect are observed in the SRIA. Similarly, for the levelized cost of hydrogen, addressing issues such as discount rate and lifespan is essential to ensure consistency and comparability across assessments.

In the case of criticality indicators, it is crucial to adopt the definition proposed by the European Commission on critical and strategic materials.[59] Additionally, clear methodologies for estimating supply risk and economic importance factors must be specifically developed for hydrogen technologies. The indicators and methodology proposed by the SH2E[60] project, provides a valuable reference point in this regard.

Clarifying the definition of social and circularity indicators would require considerable effort and the involvement of various stakeholder groups. This task could be part of research objectives of relevant EU stakeholders. For example, determining the scope of the supply chain for social indicators and establishing clear definitions for terms such as recyclable, recycled, renewable, and by-products are important steps in this process.

Table 3 Indicators proposed for project/programme monitoring

Dimension	Indicator
Environmental	Those proposed by the Environmental Footprint methodology
Criticality	Content of critical materials (%, g/kg H_2),
	Content of strategic materials (%, g/kg H_2).
Economic	CAPEX
	OPEX*
	Levelized cost of hydrogen*
Social*	Forced labour
	Child labour
	Women in the sectoral labour force
	Gender wage gap

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[59] European Critical Raw Materials Act. COM(2023) 160 - Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials.
[60] SH2E project. www.sh2e.eu

Dimension	Indicator
	Health expenditure
Circularity*	Recyclable materials content (%).
	Recycled materials content (%).
	Renewable materials content (%)
	By-product utilization - Percentage of by-products or co-products generated during hydrogen production that are reused, recycled, or valorised
*Further definition is required	

Conclusions

Conclusions

The EHS&CP has a key role in supporting the integration of sustainability and circularity in the clean hydrogen sector, which is in line with the European Green Deal and other EU policies and strategies. The methodological approach outlined in this document addresses critical areas, including analyses of policy initiatives, impact of large-scale hydrogen adoption and the integration of sustainability and circularity indicators.

While the EU has made great progress in promoting sustainability and circularity through the key initiatives such as the European Green Deal and RED II & III, **gaps persist in the policy framework and certification standards** related to hydrogen. Clear and consistent standards are needed to foster the growth of the hydrogen economy across sectors.

In this regard, the large-scale adoption of hydrogen may offer significant advantages such as decarbonising of hard-to-electrify sectors, enhancing energy security, creating jobs, improving air quality, and enabling energy storage. However, challenges including **resource intensity** (water & critical materials**), cost competitiveness, technological limitations**, and **safety** concerns must be addressed through robust certification and standards frameworks.

To ensure the sustainability and circularity of the entire hydrogen value chain, a set of indicators needs to be established. **Sustainability and circularity indicators** for hydrogen can refer to various aspects of the production, utilisation stage and overall life cycle. Key indicators may include **hydrogen production carbon intensity, water usage, land use, waste heat utilisation, leakage rates**, and **mineral resource scarcity**. In this regard, the life-cycle perspective is pivotal, and the LCA methodology offers important support. By setting appropriate indicators, the EHS&CP can support the development of standardised practices and certification systems to ensure the sustainability and circularity is integrated along the hydrogen value chain.

Furthermore, alignment with international standards, such as ISO hydrogen standards (see Annex II), can facilitate interoperability and harmonisation across global hydrogen markets. Collaborative efforts with partners such as the United States, which is developing metrics to evaluate hydrogen deployment sustainability impacts as part of the National Clean Hydrogen Strategy, will enhance cross-border cooperation and knowledge exchange. This strategy, similar to the RFNBO classification in the EU, is based today solely on CO_2 emissions-related impact.

In conclusion, further work is needed in analysing existing policies, looking for improvements, adopting and setting sustainability indicators, and promoting knowledge sharing within the hydrogen industry. Addressing these aspects, will significantly contribute to the development of a clean, sustainable, and circular hydrogen economy in Europe.

Annex I Sustainability and Circularity Indicators

Environmental dimension
Indicator
Climate change (kg CO_2 eq)
Climate change-Biogenic (kg CO_2 eq)
Climate change-Fossil (kg CO_2 eq)
Hydrogen Production Carbon Intensity ($kgCO_2/kgH_2$)
CO_2 Specific Emissions avoided ($kgCO_2/kgH_2$)
Acidification (mol H+ eq)
Ecotoxicity, freshwater (CTUe)
Ecotoxicity, freshwater_inorganics (CTUe)
Ecotoxicity, freshwater_organics (CTUe)
EF-particulate Matter (disease incidence)
Eutrophication, freshwater (kg P equivalents)
Eutrophication marine (kg N equivalents)
Eutrophication, terrestrial (mol N equivalents)
Human toxicity, cancer (CTUh)
Human toxicity, cancer_inorganics (CTUh)
Human toxicity, cancer_organics (CTUh)
Human toxicity, non-cancer (CTUh)
Human toxicity, non-cancer_inorganics (CTUh)
Human toxicity, non-cancer_organics (CTUh)
Ionising radiation, human health (kBq U235 eq)
Land use, dimensionless (pt)
Land use change emissions (tCO_2 eq, tCO_2 eq/ha, tCO_2 eq/ha·year)
direct Land Use Change (tCO_2 eq, tCO_2 eq/ha, tCO_2 eq/ha·year)
indirect Land Use Change (tCO_2 eq, tCO_2 eq/ha, tCO_2 eq/ha·year)
Ozone depletion (kg CFC11 eq)
Photochemical ozone formation - human health (kg NMVOC eq)
Resource use, fossils (MJ)
Quantity of chemicals in REACH
Resource use, minerals and metals (kg Sb eq)

Environmental dimension
Water use (m^3-world eq, L/kg H_2)
Water scarcity (m^3-world eq)
Water degradation
Hydrogen Green Index $GI = \frac{E_{from-RES}\,(MWh) + E_{from-grid,lc}(MWh) + E_{from-grid,Ac}(MWh) \cdot RES\ share\ in\ grid(\%)}{E_{total}(MWh)}$

Criticality dimension
Indicator
Content of critical materials (%, g/kg H_2)
Content of strategic materials (%, g/kg H_2)
SR*EI (Supply Risk·Economic Importance)
Mancini et al. $PCL = \sum_{i=1}^{n} \frac{SR_i}{P_i} \cdot m_i$
SH2E $PCL = \sum_{i=1}^{n} \frac{SR_i}{P_{EU,i}} \cdot m_i$
Ecoreport tool $PCL = \sum_{i=1}^{m} \frac{MCL_{Sb}}{C_i \cdot SI_{SR,i} \cdot IR_i \cdot (1 - RIR_i)} \cdot m_i$
GeoPolRisk Mid-Point $PCL = \sum_{i=1}^{n} HHI_i \cdot WGI_{I,P_{Int.},i} \cdot p_i \cdot m_i$
GeoPolRisk End-Point $PCL = \sum_{i=1}^{n} HHI_i \cdot WGI_{I,P_{Int.},i} \cdot p_i \cdot \boldsymbol{\varepsilon_i} \cdot m_i$

Economic dimension
Indicator
CAPEX
OPEX
Levelized Cost of Hydrogen

Economic dimension
Total ownership cost
Cost of avoided CO_2 (€/ton CO_2 avoided)
Net present value
Internal rate of return
Pay-back time
Eco-efficiency
Externalities

Social dimension	
Indicator	
Stakeholder worker	Freedom of Association and Collective Bargaining
	Child Labour
	Fair Salary
	Forced Labour
	Equal opportunities/Discrimination
	Women in the sectoral labour force
	Men in the sectoral labour force
	Gender Wage Gap
	Health and Safety
	Social Benefits/Social Security
	Working Hours
Stakeholder local community	Access to material resources
	Access to immaterial resources
	Delocalization and Migration
	Cultural Heritage
	Safe & healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
Stakeholder consumer	Health & Safety
	Feedback Mechanism
	Consumer Privacy
	Transparency

Social dimension	
	End of life responsibility
Stakeholder society	Public commitments to sustainability issues
	Contribution to economic development
	Prevention & mitigation of armed conflicts
	Technology development
	Corruption
Value chain actors, not in consumers	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

Circularity
Indicator
Renewable materials content (%)
Recycled materials content (%)
Recyclable materials content (%)
Total waste per product, waste generation rate (kg/MW)
Conversion efficiency - Percentage of feedstock converted into hydrogen
Byproduct utilization - Percentage of byproducts or co-products generated during hydrogen production that are reused, recycled, or valorised
Waste recycling rate (%)
Zero waste initiatives
Water recycling rate (%)
Material recovery rate (closed loop systems) (%)
Waste Heat to valuable applications (KWh Heat/kgH_2)

Annex II Hydrogen Standards

Table 4 ISO Hydrogen Standards

Standard	Description/Summary
Hydrogen Safety	
ISO/TR 15916	Covers general safety guidance for hydrogen systems
ISO 26142	Gas detection for stationary applications
Hydrogen Production	
ISO 22734, Part 1 and 2	Hydrogen production utilizing the water electrolysis process. Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications - Part 1: General requirements, test protocols and safety requirements (ISO/TC 197/WG 34 (ISO 22734-1) Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications - Part 2: Testing guidance for performing electricity grid service (ISO/TC 197/WG 32 (ISO 22734-2)
ISO 14687	Product specification/ hydrogen quality
ISO/AWI 19870 (under development) will replace ISO/TS 19870:2023	Methodology for determining the greenhouse gas emissions. Hydrogen technologies. Part 1: Emissions associated with the production of hydrogen up to production gate
ISO 16110, Part 1	Test methods for hydrogen generators using processing technologies
ISO 114687	Hydrogen fuel quality - document number: ISO/TC/WG 27
Hydrogen Storage	
ISO 16111	Transportable gas storage devices for hydrogen (specifically using metal hydride)
ISO 19884	Hydrogen cylinders and tubes for stationary storage of gaseous hydrogen
Hydrogen Transportation	
ISO 11114, Part 4	Transportable gas cylinders- compatibility of cylinder and valve materials with gas contents. Part 4: Test methods for selecting steels resistant to hydrogen embrittlement