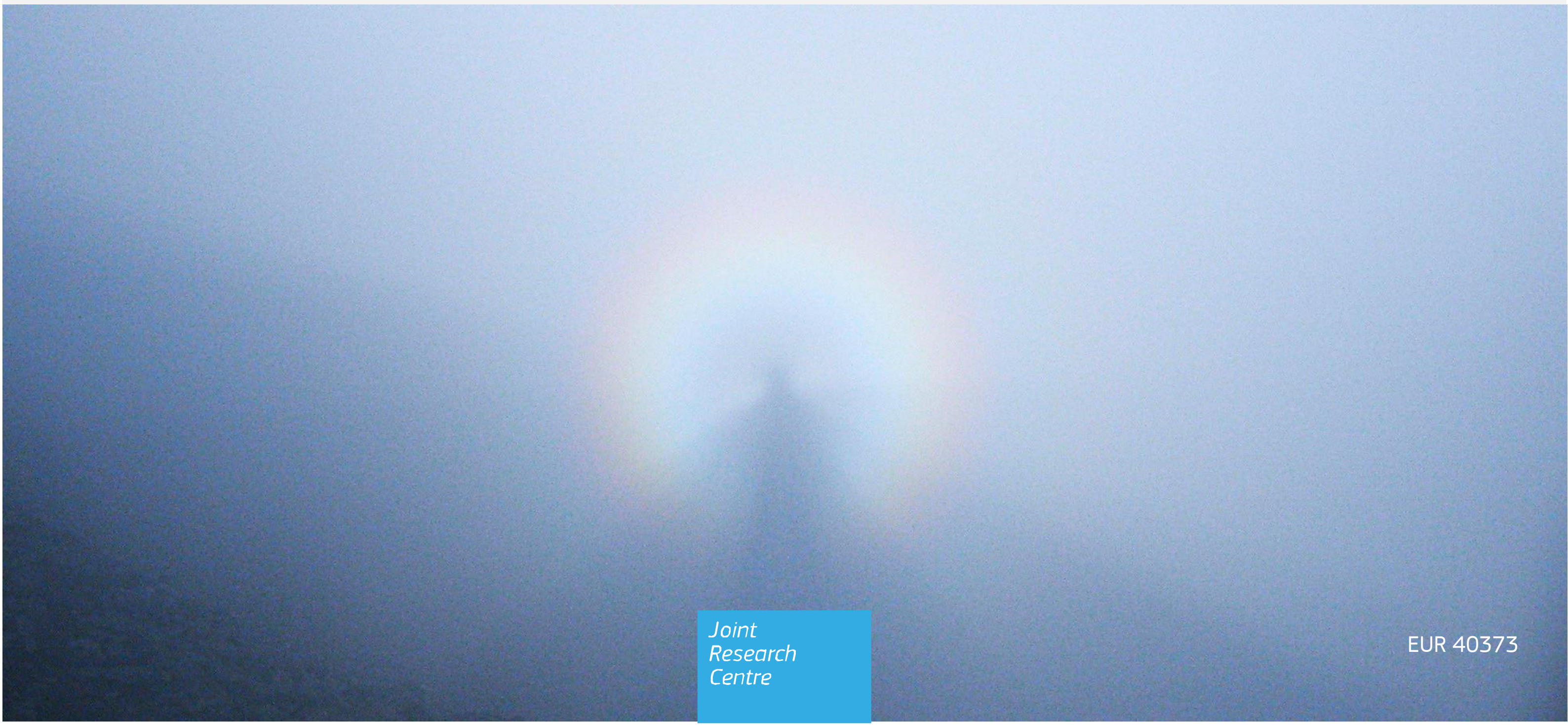
ISSN 1831-9424

A conceptual framework for assessing and monitoring social risks and impacts related to hydrogen technologies and their value chains

Zamagni, A., Mancini, L., Eynard, U., Arrigoni, A.
Mathieux, F.

2025



EUR 40373

This document is a publication by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC138850

EUR 40373

PDF ISBN 978-92-68-29191-7 ISSN 1831-9424 doi:10.2760/8349525 KJ-01-25-361-EN-N

Luxembourg: Publications Office of the European Union, 2025

© European Union, 2025

The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union permission must be sought directly from the copyright holders.

How to cite this report: Zamagni, A., Mancini, L., Eynard, U., Arrigoni, A. and Mathieux, F., *A conceptual framework for assessing and monitoring social risks and impacts related to hydrogen technologies and their value chains,* Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/8349525, JRC138850

Contents

Abstract

The proposed conceptual framework aims at assessing social risks, impacts and benefits generated by hydrogen technologies and their value chains, addressing technologies at different Technology Readiness Levels. Risks, impacts and benefits are captured at two levels: technology-specific impacts and impacts at macro level. The framework is rooted into the life cycle approach, and proposes six social areas of concerns (i.e., social topic of interest for society) and a set of social indicators for measuring them. Most of the indicators can already be measured and evaluated, and only a limited set requires further operationalization. Addressing all the areas of concerns of the framework as well as the potential benefits can contribute to increase the acceptability of the hydrogen technologies by stakeholders. The application of the framework to all hydrogen-related projects funded by the Clean Hydrogen Joint Undertaking programme, coupled with the financial value of the projects, can be the basis for defining Key Performance Indicators for measuring the social value generated by the Clean Hydrogen Joint Undertaking programme.

Acknowledgements

This report was prepared under the framework contract between the Directorate-General JRC of the European Commission and the Clean Hydrogen Joint Undertaking (Clean Hydrogen JU). The authors would like to express their gratitude to the Clean Hydrogen JU for its financial support and Alberto Garcia Hombrados for his encouragement. Additionally, the authors extend their thanks to Eveline Weidner (JRC C.1) and the European Hydrogen Sustainability and Circularity panel for reviewing the document.

Authors

Alessandra Zamagni [a], Lucia Mancini [b], Umberto Eynard [c], Arrigoni Alessandro [d], Fabrice Mathieux [c]

[a] Ecoinnovazione Srl, Bologna, Italy

[b] Trasys International, Network Research Belgium S.A. (NRB), Herstal, Belgium *(the work has been carried out at and on behalf of JRC)*

[c] European Commission, Joint Research Centre (JRC), Ispra, Italy

[d] European Commission, Joint Research Centre (JRC), Petten, Italy

1 Introduction

The production and use of energy account for more than 75% of the EU's greenhouse gas emissions (IEA 2020). Energy transition towards low carbon technologies is then needed to help decarbonize the EU's economy and reduce its dependence on imported fossil fuels to reach the EU's long-term strategy of carbon neutrality by 2050. For this reason, the European Commission adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels (EC 2019); (EC 2021).

The RePower EU Plan (EC 2022a), launched in response to the shock on the energy markets caused by the Russia's invasion of Ukraine, reinforced the need to accelerate on the energy transition while promoting clean energy production. The plan also aims at enhancing efficiency throughout the European Union, implementing a range of energy-saving measures and promoting energy-conscious practices. Moreover, diversifying its energy mix and decreasing reliance on fossil fuels, the EU can lessen its vulnerability to geopolitical disruptions.

Role of hydrogen in the decarbonization

In the transition to clean energy technologies, hydrogen can play a crucial role in decarbonizing various sectors in the EU. Hydrogen can, in fact, be produced generating low greenhouse gas emissions, for instance, via water electrolysis powered by low-emissions electricity or via fossil fuels with carbon capture and storage. However, this is currently not the case, with global hydrogen production emitting almost 1 Gt of CO2 in 2023, with less than 1% of the hydrogen being generated through low-emissions methods (IEA Global Hydrogen Reviews). Nevertheless, low-emissions hydrogen yearly production could reach almost 50 Mt by 2030 based on announced projects (IEA Global Hydrogen Reviews), with the EU aiming to produce 10 Mt of renewable hydrogen and to import a similar amount (REPowerEU Strategy). To minimize the climate impact of a hydrogen economy, hydrogen losses to the atmosphere need to be prevented as well. Although hydrogen is neither intentionally emitted to the atmosphere when used nor a direct greenhouse gas, hydrogen losses to the atmosphere will impact the lifetime of other greenhouse gases, namely methane, ozone, and water vapour, indirectly contributing to the increase of the Earth's temperature in the near-term (Arrigoni & Diaz 2022).

If renewable sources are used, the use of hydrogen could also reduce the dependence on imported fossil fuels. However, it is important to note that hydrogen supply chains have typically an international dimension, and that a hydrogen-based economy is subject to dependencies and supply chain vulnerability as well. For instance, the EU supplies only 2% of the raw materials required in electrolyser production (Bolard et al. 2023).

Hydrogen in Europe is expected to play a key role as an energy carrier in decarbonizing hard-to abate sectors, where other alternatives might be unfeasible or costly, such as heavy industry and long-range transport. In the industry, hydrogen is envisioned as a replacement for fossil fuels in e.g., steel production and chemical manufacturing. In the transport sector, the use of hydrogen in internal combustion engines and in fuel cells have been explored for heavy-duty vehicles, trains and maritime transport. Moreover, hydrogen-based synthetic fuels are considered as the only available solution to decarbonize aviation (Buffi et al. 2022). Additionally, hydrogen can facilitate the integration of variable renewables into the electricity grid, providing a valuable energy storage solution over extended periods.

The EU has supported research and innovation on hydrogen for many years, leading to the development of hydrogen technologies in promising applications and to the achievement of EU global leadership for electrolysers, hydrogen refuelling stations and megawatt-scale fuel cells (Clean Hydrogen Partnership[1]).

Social impacts of hydrogen technologies

The transition to clean energy technologies, including hydrogen, has effects not only on environmental impacts but it has also significant social implications that require to be identified and measured. According to some authors, research on the societal effects of the hydrogen transition is in its infancy (Hanusch, F., & Schad, M. (2021 Almaraz et al. 2023), and criteria to support a social assessment of hydrogen technologies are not fully developed yet. Robust methodologies have to be developed for assessing the social benefits and impacts of hydrogen technologies along the whole value chain, beyond social acceptance and including the supply of critical raw materials, whose deployment is expected to increase significantly.

The Joint Research Centre (JRC) supports the Clean Hydrogen Joint Undertaking (Clean Hydrogen JU) in developing and making available data collected from projects and continues supporting the development of guidelines for assessing social life cycle impact of hydrogen technologies. In this context the JRC developed a conceptual framework for assessing and monitoring the social impacts related to the implementation of hydrogen-based technologies and their value chains in the transition towards climate neutrality at EU scale. This framework provides the theoretical basis for the definition of the methodology, and related methods and models that make the framework applicable for the social assessment of technologies, with a focus on hydrogen. Ultimately, the framework and the methodology are intended to be used by Clean Hydrogen JU for evaluating the potential social impacts and consequences of hydrogen-related technologies developed within projects of the Horizon 2020 Fuel Cells and Hydrogen Joint Undertaking (FCH-JU), in alignment with the mission to promote and coordinate research, development and innovation of clean hydrogen technologies.

This report describes the proposal of this conceptual framework for the assessment of social impacts of hydrogen technologies, identifies the methodology requirements and suggests indicators for measuring social risks, impacts and benefits. A detailed definition of the methodology, as well as procedural guidance for the application of the framework, are not within the scope of this report. Hydrogen has a wide range of applications across various industries due to its clean-burning properties and versatility. For example, it can be used as energy carrier both in combustions and in fuel cells, it can be used as industry feedstock for ammonia and methanol production and petrochemical refining. It allows energy storage and can be used in transportation in fuel cell electric vehicles or as alternative to conventional fuels. The scope of this report is limited to hydrogen as a clean energy carrier.

After the description of the principles of the conceptual framework (section 2), and the working method (section 3), an analysis of the state of the art of the social assessment of energy and hydrogen technologies is provided in section 4. This is coupled with an analysis of the social dimension of energy, as defined in several EU policies. The conceptual framework is then presented in section 5, in terms of its ontological, epistemological and methodological characteristics. The methodology is then presented, which is built upon the life cycle approach and the skeleton of the Social Life Cycle

---

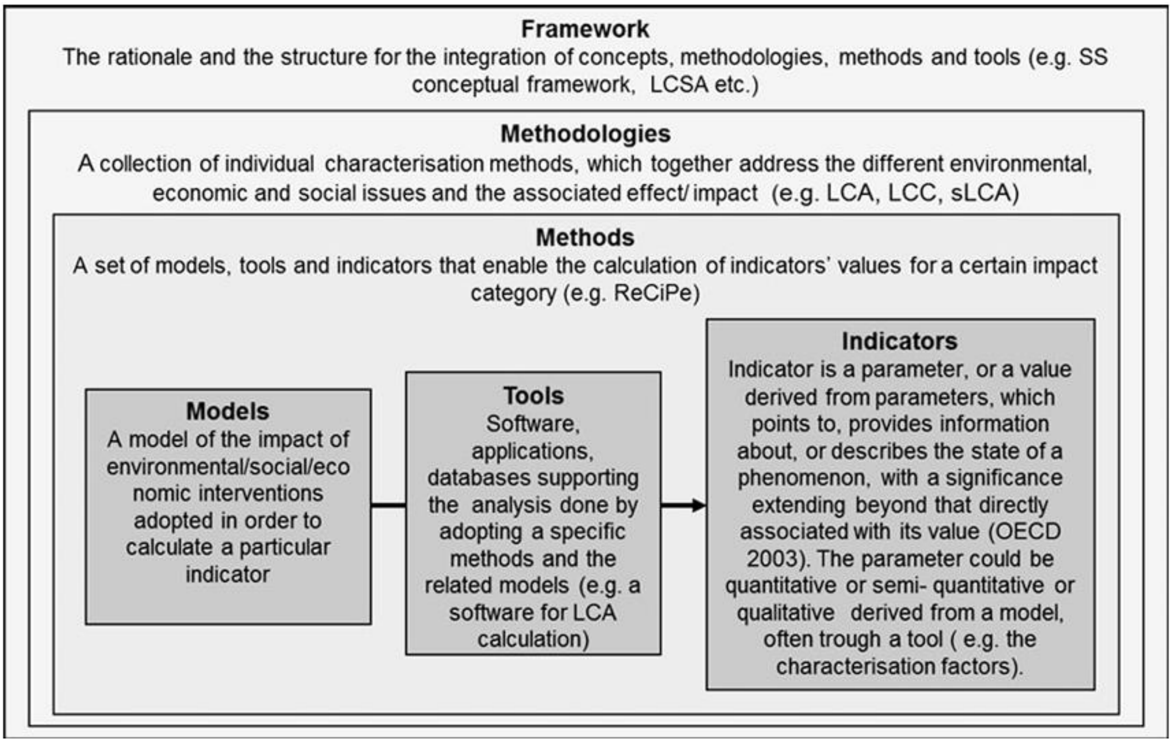
[1] https://www.clean-hydrogen.europa.eu/about-us/our-story_en

Assessment. This is complemented by a list of social aspects and indicators for the assessment of hydrogen technologies. Finally, conclusions are drawn in section 6, highlighting also limitations and further steps for operationalizing the framework.

2 A conceptual framework for the social assessment of hydrogen technologies

A conceptual framework aims at providing the context and the theoretical rationale for examining the problem, developing hypotheses, making observations, defining concepts and interpreting the findings. It is the skeleton of a study and includes concepts, assumptions, values and theories that guide the research questions (Ravitch and Riggan 2016). Defining a conceptual framework is then the first step of development of full-package assessment, i.e., a toolbox consisting of methodology (ies) and related methods, models and tools, as illustrated in Figure 1.

Figure 1. Relationships among framework, methodologies, methods, models, tools and indicators.



Framework
The rationale and the structure for the integration of concepts, methodologies, methods and tools (e.g. SS conceptual framework, LCSA etc.)

Methodologies
A collection of individual characterisation methods, which together address the different environmental, economic and social issues and the associated effect/ impact (e.g. LCA, LCC, sLCA)

Methods
A set of models, tools and indicators that enable the calculation of indicators' values for a certain impact category (e.g. ReCiPe)

Models
A model of the impact of environmental/social/economic interventions adopted in order to calculate a particular indicator

Tools
Software, applications, databases supporting the analysis done by adopting a specific methods and the related models (e.g. a software for LCA calculation)

Indicators
Indicator is a parameter, or a value derived from parameters, which points to, provides information about, or describes the state of a phenomenon, with a significance extending beyond that directly associated with its value (OECD 2003). The parameter could be quantitative or semi- quantitative or qualitative derived from a model, often trough a tool (e.g. the characterisation factors).

Source: Sala et al. 2013

A practical implication of a conceptual framework is that it provides the rationale for the assessment and defines the underlying social theories that inform a coherent and robust identification and definition of social indicators.

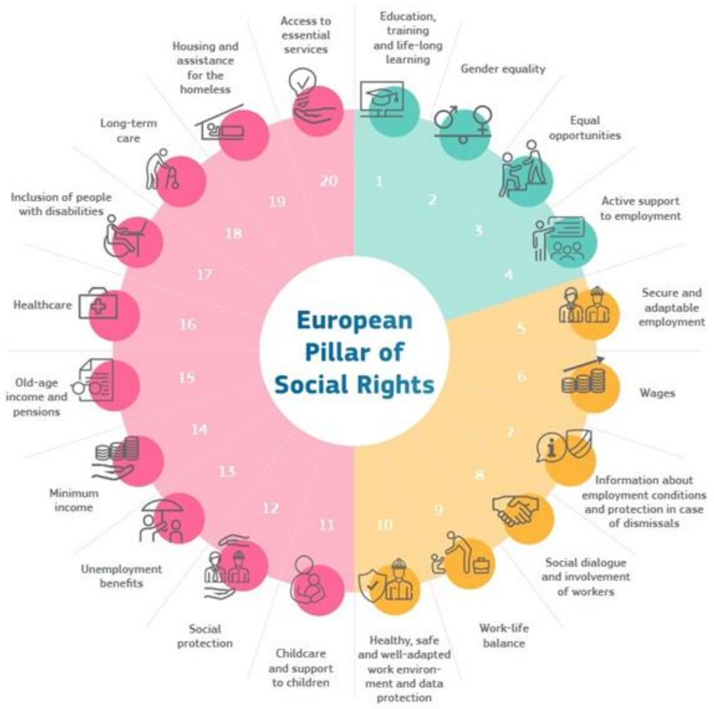
2.1 Principles of the conceptual framework

The conceptual framework for the assessment of social impacts of energy technologies lays its foundations in the sustainability science, and ultimately it is conceived to support the implementation of the hydrogen energy strategy (EC 2020) in line with the European Pillar of Social Rights (EC 2017) (Figure 2) and the Sustainable Development Goals, thus ensuring:

- Equal opportunities and access to the labour market (principles 1-4 in Figure 2).
- Fair working conditions (principles 5-10 in Figure 2).
- Social protection and inclusion (principles 11-20 in Figure 2).

- Affordable and clean energy (Sustainable Development Goal 7), namely "access to affordable, reliable, sustainable, and modern energy for all." (UN General Assembly, 2015). This definition emphasizes the importance of affordability, reliability, and modernity while highlighting the need for sustainability.

Figure 2. European pillars of social rights



Source: EC, The European Pillar of Social Rights in 20 principles - Employment, Social Affairs & Inclusion - European Commission (europa.eu)

Finally, the framework is meant to support the identification of measures on how to improve responsible value chains, including manufacturing of critical and strategic raw materials.

The development of the conceptual framework is guided by principles, which have been defined taking into account existing frameworks for social and sustainability assessment relevant for this purpose (Mancini et al. 2023); (Sala, Farioli, and Zamagni 2013a; 2013b); (Valdivia et al. 2021); (Eizenberg and Jabareen 2017); (László et al. 2018), namely:

- **Life cycle thinking**: the adoption of life cycle thinking implies that direct and indirect social impacts are considered, thus avoiding potential burden shifting across different stages and stakeholders along the value chain. The practical implication is that the whole life cycle of hydrogen technologies is considered, i.e., from resource extraction to processing, construction of the plant and related infrastructures, operation, maintenance, use and end of life. This is in line with several previous and ongoing EU environmental and energy policies, as highlighted in Sala et al. (2021), in which the life cycle thinking is a key principle.

- **Transparency**: a clear and understandable documentation of the assumptions, value choices, data and modelling choices ensure reproducibility and a robust interpretation of the results (Pikhola et al. 2023); (Valdivia et al. 2021). This is even more crucial for a social assessment, where data and information in some cases are filtered by the opinion and judgment of stakeholders, who might be affected by their values, beliefs and context in which they are embedded.

- **Relevance**: the social impacts to be addressed in the framework are those that are relevant for energy technologies, with a focus on hydrogen, for the specific decision-context and for the stakeholders using that information. Relevance is used as synonym of materiality (UNEP 2020).

- **Adequacy of scope**: given the ongoing research and development in the field of hydrogen technologies, the framework should be able to address technologies with different level of maturity, i.e., any Technology Readiness Level (TRL). TRLs are measured from 1 (basic principles observed to 9 (actual system proven in operational environment). A detailed description of each level is available at h2020-wp1415-annex-g-trl_en.pdf (europa.eu). More information on the technological scope of the conceptual framework is addressed in Section 2.2.

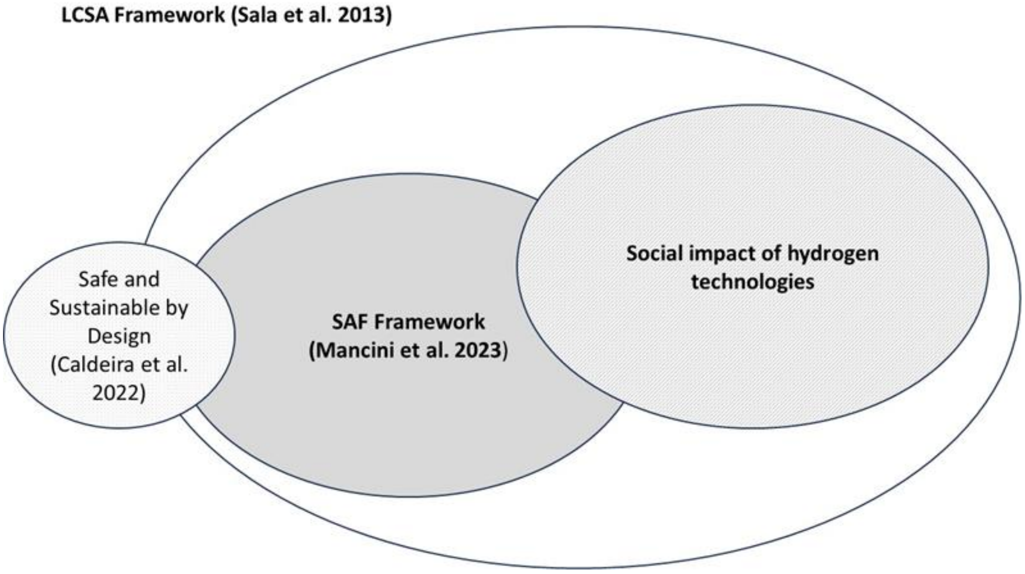
  According to the level of maturity of the technology considered in the assessment, the goal of the study might change: at the industrial scale, with a technology already up and running, potential social impacts can be assessed with data that reflect the effects already experienced by stakeholders. At low TRLs, the focus is on understanding where and which potential social impacts might arise, to guide the further scale-up and also the identification of suitable locations where to install and deploy the technology. Therefore, different time frames are considered, i.e., the present corresponding to the status of development of the technology, and the future, in which the technology will be functioning. The identification of plausible future scenarios for the technology development is thus necessary and should be supported by the conceptual framework.

  The scope of the assessment entails also the scale of the impacts (local vs global and the geographical scale). Regarding the scale, social impacts at both local and global level should be addressed by the framework: the local level is of particular relevance, given that social impacts are context specific, and can affect different types of stakeholders. Impacts at global level entails society at large and might be generated when there is a high level of technology penetration and pervasiveness.

  For what concerns the geographical scale, a global perspective is needed in the case of hydrogen technologies. The supply chain of hydrogen has an international dimension, concentrated in extra-EU countries: platinum-group metals are commonly used for manufacturing catalysts used in fuel cells and electrolysers, and South Africa is dominating the production, followed by Russia and Zimbabwe. These are the general global production shares, however, different shares may exist when looking at specific platinum group metal (Trinomics and Artelys, 2021) (RMIS, 2025). For R&D activities and technologies manufacturing, Europe is highly competitive (EC 2020): Europe is one of the major suppliers of processed materials and components for fuel cells and electrolysers (Trinomics and Artelys, 2021) (Carrara et al., 2023).

- **Stakeholders' consideration**: social impacts are "changes—intended or unintended, anticipated or unanticipated, positive or negative—in the way people live, experience, sustain, and function within their society" (Costa and Pesci 2016). Stakeholders are then the backbone of any assessment of social impacts, but they play not only a "passive" role (those who suffer or benefit) but also an "active" one, by providing information and data needed for the analysis. In addition, in the context of a technology assessment, they are also those who play a pivotal role in the "go-no go" decision of technology development, through the acceptance process.
- **Comparability**: the comparison among hydrogen technologies is a requirement of Clean Hydrogen JU, also supporting the monitoring and evaluation of its multiannual programme objectives and targets. Caution is necessary when comparing technologies with different level of maturity: different levels of information on the technologies, different data quality and understanding of the context might hamper the comparison. It is important to point out that the social impacts of hydrogen technologies, and of technologies in general, is strictly linked to the specific application and condition of use of the technology itself, i.e., the function provided by the technology, together with the context: these aspects have to be taken into account for ensuring a fair comparability among technologies.
- **Coherence**: while being focused on the social dimension only, the conceptual framework has to be coherent with frameworks for sustainability assessment: the main references are represented by the framework for Life Cycle Sustainability Assessment (LCSA) developed by (Sala, Farioli, and Zamagni 2013a; 2013b) rooted into the sustainability science discipline, and by the Sustainability Framework for Energy Technologies by (Mancini et al. 2023). The three frameworks share the overarching vision and key principles, while clearly the scope differs, and this has a direct implication on the definition of the methodology for implementing the framework. The relationships among the three frameworks are illustrated in Figure 3.

Figure 3. Relationship among the main frameworks for sustainability and social assessment. The framework of Mancini L et al. (2023) has considered also the design principles defined in Caldeira et al. (2022).

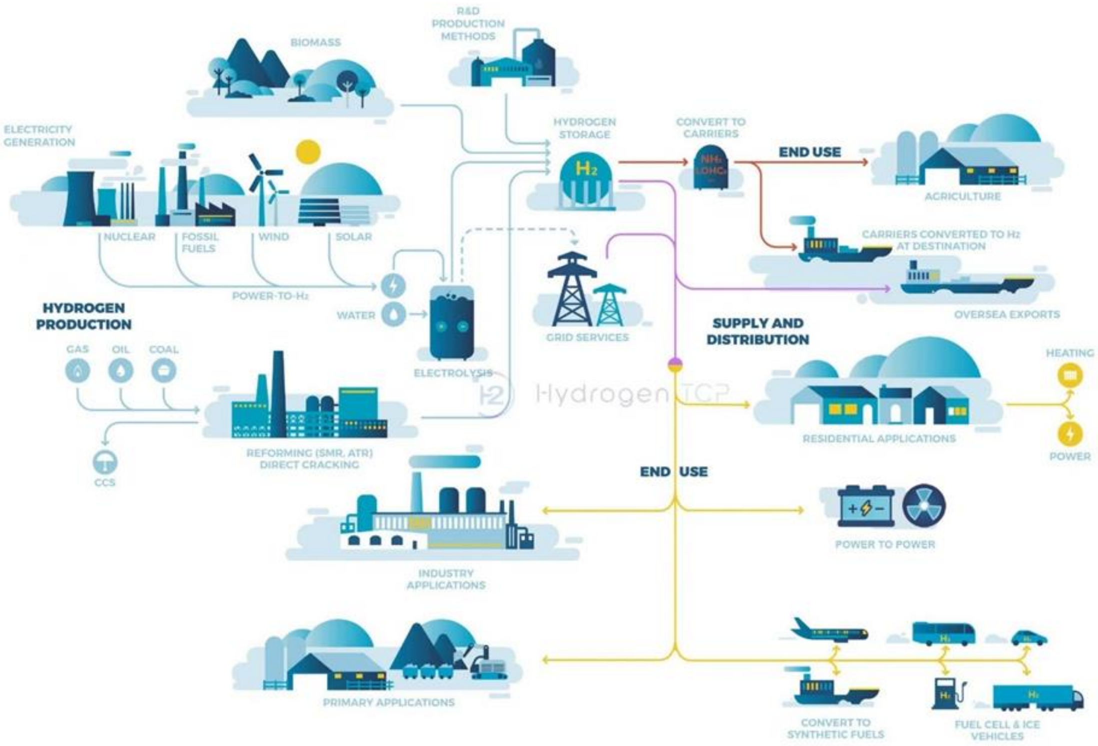


Source: authors' elaboration.

2.2 Technological scope of the conceptual framework

A simplified representation of the technological scope of the framework, and of the hydrogen technologies covered, is described in Figure 4. The whole hydrogen value chain is addressed, namely hydrogen production, transport and storage, use, and end-of-life, with different level of technology development. Therefore, all the technologies presented in this section fall within the scope of this conceptual framework.

Figure 4. Simplified scheme of hydrogen economy.



Source: IEA https://www.ieahydrogen.org

2.2.1 Hydrogen production technologies

Hydrogen production is the first step in the hydrogen value chain. Although there are some natural sources of hydrogen, such as underground reservoirs and hydrogen-rich gases, most hydrogen is currently produced from other energy sources, such as fossil fuels, biomass, or renewable energy. Hydrogen can be produced via many different pathways, using different energy sources and different production technologies. In Figure 5, the TRL of the main hydrogen production technologies is presented together with the one of other clean energy technologies. The scale of the TRL is the one defined by IEA, from the concept stage (TRL 1) to the scale up of the technology solution (TRL 11). The main technological options include:

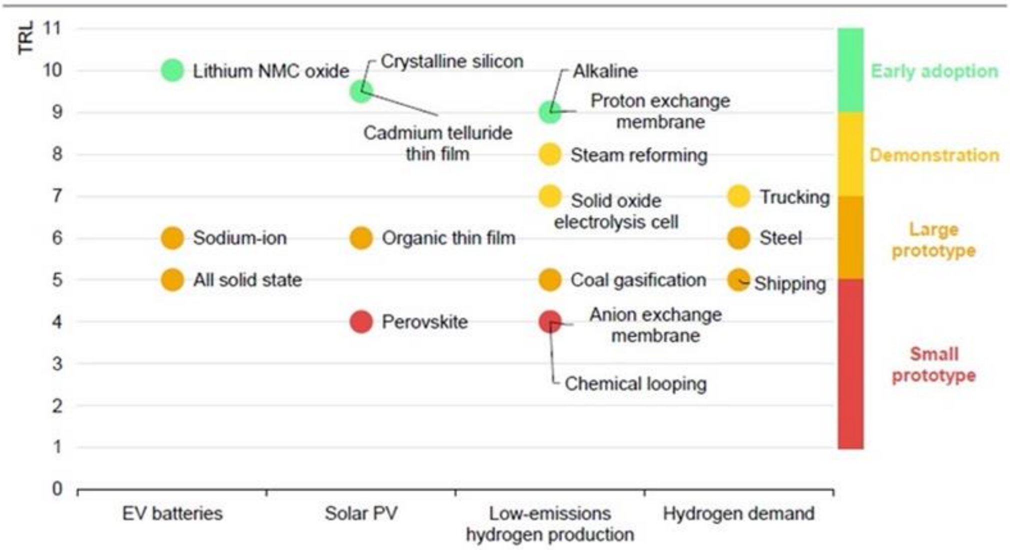
- **Water electrolysis**, which is the most mature and promising low-emission hydrogen production technology. Electrolysis splits the water molecule into hydrogen and oxygen via electrical energy, consuming approximately 50-55 kWh per kg of hydrogen. The most advanced electrolysis technologies are alkaline and proton exchange membrane (PEM), which have been deployed in demonstrations reaching a power of hundreds of MW. Alkaline electrolysis is a cost-effective and stable technology for hydrogen production that does not require noble metal catalysts, but it has limitations in terms of operational flexibility and low current densities. However, advancements are being made to improve its flexibility for more efficient integration with renewable energy sources (Bolard et al. 2023). On the other hand, PEM electrolysis performs better under dynamic conditions, making them well-suited for integration with renewable energy sources. However, PEM electrolysis is hindered by durability issues and high costs due to the use of expensive platinum group metals like platinum and iridium.

- **Anion Exchange Membrane (AEM) electrolysers**, which combine the benefits of alkaline and PEM electrolysers. Solid Oxide electrolysers (SOE) can achieve high efficiency at high temperatures, but face challenges related to material durability, slow ramp rates, and limited operational flexibility.
- **Proton Conductive Ceramic electrolysis (PCCEL)** is a promising technology: operating at lower temperatures than SOE but requiring further development and research (Bolard et al. 2023).
- **Conventional thermochemical processes**, such as reforming, partial oxidation, gasification, or hydrogen production as by-product from refining operations, ethylene and styrene production, and from chlor-alkali electrolysis. In Europe, approximately 90% of hydrogen is produced via steam methane reforming[2]. These thermochemical processes would not help towards the decarbonisation targets unless renewable feedstock were used (i.e., biomass) and/or if the carbon dioxide generated during the process were captured and stored. The benefit of reforming with carbon capture is that the reforming technology is mature, allowing large scale productions. There is however uncertainty over CO_2 storage and transportation costs. At the same time, this technology would not reduce the EU dependence from imported fossil fuels.
- **Methane splitting and waste-to-hydrogen** are less mature technologies that could provide low-emission hydrogen. The former refers to the dry decomposition of methane, generating solid carbon as a by-product. The latter refers to technologies transforming waste, either biological or non-biological, to hydrogen via different processes, such as pyrolysis and gasification.

---

[2] https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/hydrogen-production

Figure 5. TRLs of leading clean energy technologies[3].



Source: IEA (2022)

2.2.2 Storage

Not all methods of storage are currently feasible under all circumstances. In particular, to enable transportation and use, hydrogen needs to be conditioned (e.g., compressed or liquefied) and stored. Moreover, different technologies exist for storing hydrogen, with different level of maturity. Each options has its own challenges, for example:

- Hydrogen can be stored above ground as a gas, a liquid, or through interactions with solid materials. However, storage of hydrogen as a gas typically requires high-pressure tanks, which are typically used for storing hydrogen on vehicles.

- On the other hand, storing hydrogen as a liquid requires very low temperatures (-253°C) in cryogenic tanks.

- In addition, metal or chemical hydrides allow hydrogen storage at high volumetric and gravimetric density at low pressures, but cyclability[4], a suitable heat supply and thermal management have proven to be particularly challenging for this storage option for several reasons, which include material degradation, kinetics and heat management, to mention some. t

- Large amounts of gaseous hydrogen can also be stored in underground salt caverns. The technology is at high TRL, but more fundamental research is needed to investigate hydrogen compatibility with porous rock media (Clean Hydrogen Partnership 2023).

---

[3] In the figure, the scale of the TRLs is the one defined by IEA, that goes from the concept stage (TRL 1 to scaling up of the technology solution (TRL 11). Details are available at https://www.iea.org/reports/innovation-gaps. In all the other parts of the document, the TRLs are defined according to the original definition by NASA (scale 1-9), which was introduced in EU funded projects in 2012.

[4] Cyclability is the ability of a storage material or system to repeatedly absorb and release hydrogen over multiple cycles without significant degradation in performance.

2.2.3 Transportation

To connect the hydrogen production site and the point of use, hydrogen needs to be transported. Large-scale hydrogen delivery over long distances is a significant challenge due to hydrogen's low energy density. For this purpose, hydrogen can be compressed and transported by pipelines, or delivered by trucks, ships, and rail in a compressed or liquefied form. However, each of these modes must take into account different factors that may sometimes be complicated to address.

For distances over 3,000 km, pipeline transfer is likely to be less cost-effective than shipping compressed or liquid hydrogen or using chemical carriers (Ortiz Cebolla et al. 2022). As chemical carriers, ammonia, methanol, synthetic natural gas, and liquid organic hydrogen carriers (LOHC) are usually considered. While ammonia production and transport are well-established, its cracking process to release hydrogen still needs to be scaled up.

LOHC, on the other hand, offers a promising alternative, as it doesn't release CO_2 during hydrogen release and can utilize existing infrastructure like oil tankers. However, a concern about ammonia as a hydrogen carrier is the need for large storages of ammonia at various points of distribution. These suits will become high hazards sites under the EU Seveso Directive and must meet strict safety performance criteria.

A key consideration for chemical carrier delivery is also the energy required for dehydrogenation (Clean Hydrogen Partnership 2023). A previous JRC study showed that the transportation of liquid hydrogen by ship is likely the most environmentally sustainable option to transport hydrogen for distance compatible with the European territory (Arrigoni et al. 2024).

In general, more research is needed on the social implications of using different carriers and the potential risks along the delivery chain.

2.2.4 Hydrogen use and applications

Finally, hydrogen can be used for several applications. Currently, hydrogen is almost exclusively used in refining and industry applications, such as ammonia and methanol production. However, decarbonisation efforts are expected to increase the use of hydrogen in new applications, such as:

- long-distance transport
- steel production (hydrogen used as a reducing agent in iron direct reduction)
- production of hydrogen-based fuels (e.g., ammonia, synthetic hydrocarbons)
- high-temperature heating in industry
- electricity storage
- electricity generation (e.g., via fuel cells).

The demand for low-emissions hydrogen increased by almost 10% in 2023, but its share remains relatively small. To accelerate growth, governments are introducing policies such as mandates, incentives, and market development tools. As a result, the demand for low-emission hydrogen is expected to reach over 6 Mt by 2030 (IEA 2024).

The technologies along the hydrogen value chain mentioned in this Section can be summarized in product categories. The EU-funded project HyPEF (*Promoting an environmentally-responsible Hydrogen economy by enabling Product Environmental Footprint studies*)[5] developed a list of 11 product categories and 14 subcategories representing the hydrogen value chain. The goal of the project is to establish a rigorous framework for evaluating the environmental impact of hydrogen technologies. The list of product categories developed by HyPEF is reported in Table 1 to provide examples of potential applications for the conceptual framework presented here (Ben Hnich et al. 2024).

Table 1. Product categories and subcategories representing the hydrogen value chain

Family	**Product category**	**Subcategory**
Technologies for hydrogen production	Technologies for hydrogen production	Thermochemical plants for hydrogen production
		Electrochemical processes for hydrogen production
Technologies for hydrogen conditioning	Compressors specific to hydrogen conditioning	
	Liquefaction units specific to liquid hydrogen production	
	Regasification units of liquid hydrogen	
Modes of hydrogen storage	Tanks for hydrogen storage	Tanks for liquid hydrogen storage
		Tanks for compressed hydrogen at moderate storage pressures
		Tanks for compressed hydrogen storage for passenger cars and tube trailers
		Tanks for compressed hydrogen storage for heavy-duty mobility
		Tanks for cryo-compressed hydrogen storage
	Sites for large-scale geological storage of gaseous hydrogen	
Modes of hydrogen transport	Vehicles and ships for hydrogen transport	Trailer trucks for liquid hydrogen transportation
		Trailer trucks for gaseous hydrogen transportation
		Large ships for hydrogen transmission
	Pipelines for hydrogen transport	Pipelines for hydrogen transmission
		Pipelines for hydrogen distribution
Hydrogen use cases	Hydrogen fuel cells intended for electricity production	
	Hydrogen fuel cells for combined heat and power generation	
	Processes requiring for heat production from hydrogen	Internal combustion engines for hydrogen-powered vehicles
		Large industrial devices for thermal energy production from hydrogen

Note :Hydrogen conditioning is not specifically addressed in this document, but it is included in this table for completeness of the technologies considered in the value chain.

Source: Ben Hnich et al. 2024

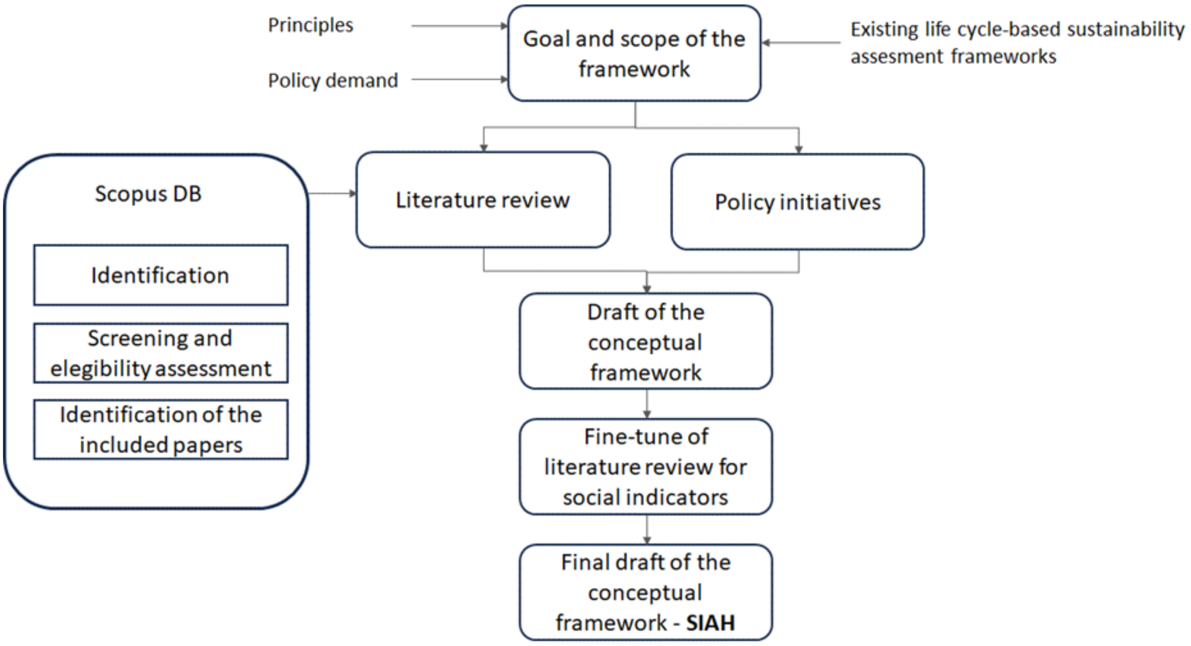
---

[5] https://cordis.europa.eu/project/id/101137575

3 Working method

An iterative approach has been adopted for the development of the conceptual framework, illustrated in Figure 6. First, the goal and scope of the framework has been defined, together with the underlying principles, based on its intended use as defined by the commissioner of the study and on the existing life cycle-based sustainability assessment frameworks, in particular the LCSA by (Sala, Farioli, and Zamagni 2013a; 2013b) and the Sustainability Framework for Energy Technologies (SAF) (Mancini et al. 2023).

Figure 6. Working method for the development of the conceptual framework.



Source: author elaboration.

Then, a literature review was carried out, aimed at identifying:

- The most promising approaches for the social impact of hydrogen technologies
- Inherent characteristics of hydrogen technologies that might have a social counterpart
- Social dimension of hydrogen and/or energy technologies in the policy initiatives, which represent the overarching goal to be achieved
- Social aspects relevant for energy/hydrogen technologies, and related indicators.

The analysis of the social dimension of hydrogen and energy technologies in the policy initiatives has taken its point of departure from the European Green Deal (EC 2019), the REPowerEU plan (EC 2022a) and the European Hydrogen Strategy (EC 2020), complemented with technical reports and position papers delivered by International Energy Agency, Hydrogen Europe and studies commissioned by the European Commission.

The literature review considered the publication in the last 20 years, under the assumptions that previous research was embedded in the following years or superseded. The following keywords were used, searched within article title, abstract and keywords within the Scopus database:

- Social AND impact AND hydrogen
- SLCA/S-LCA AND hydrogen/energy technology
- Social AND impact AND assessment AND hydrogen/energy
- Energy AND justice AND social AND assessment
- Hydrogen/Energy AND security
- Technology AND autonomy AND energy/hydrogen

Overall, more than 1300 articles were identified, covering a broad range of sources including scientific papers, dissertation thesis, discussion papers, working papers, book chapters, grey literature. Scientific journals spanned among sector-specific literature and methodological-focused journals, covering: Int J of Energy Economics; Energy, Sustainability and Society; Sustainable Energy Technologies and Assessment; Applied Energy; Int J of Hydrogen Energy; Energy Research and Social Science; Energy Procedia/Climate Policy; Int J LCA; Journal of Cleaner Production; Sustainability; Environmental Impact Assessment Review; Technology Forecasting & Social change; J of Industrial Ecology; Science of the Total Environment; Environmental Research Letters; Renewable and Sustainable Energy Review. These initial articles have been further narrowed down, by deleting duplicates and reading abstracts, to a final number of 70 articles, including grey literature, which were analysed in-depth.

Based on the outcomes of the literature and policy review, an initial draft of the conceptual framework has been outlined, in terms of ontology and epistemology criteria. Then the methodology has been defined, and social impacts and indicators for measuring them have been defined, where available.

The final conceptual framework has then been finalized, resulting in the proposal described in this technical report.

4 Social assessment of energy technologies

This chapter provides an overview of the current policy context related to the social dimension of energy technologies. It then describes the main features of the hydrogen technologies that can influence the social sphere. Finally, it delves into the main methodological approaches for the social assessment, including the Life Cycle based approaches and the Technology Assessment.

4.1 Policy context on the social dimension of energy technologies

The European Commission (EC), with the REPowerEU Plan (EC 2022a), aims at achieving an affordable, secure and sustainable energy for Europe. With this plan, the EC focuses on:

- saving energy
- producing clean energy
- diversifying energy supply to mitigate risks of potential disruption in the supply chain for securing energy provision
- securing affordable energy supply.

Together with the European Hydrogen Strategy (EC 2020), it provides a comprehensive framework to support the uptake of renewable and low-carbon hydrogen towards the overarching goal of EU decarbonisation, and to ensure that this transition is just and beneficial for all.

Security, resilience and sustainability of clean energy value chains are the paradigms of the energy transition (IEA 2022) and are also part of the key actions identified in the Strategic Energy Technology Plan (EC 2018) for research and innovation.

4.1.1 Social dimension: energy security, resilience and social sustainability

- **Energy security** entails the uninterrupted availability of energy sources at an affordable price (IEA 2022). While R&D activities and the plant manufacturing are usually carried out in Europe, the procurement of equipment, materials and components often relies on global supply chains. Thus, energy security entails also the mitigation of potential risk of disruptions in the supply chain, which in turn affects availability of components and materials needed for the technology development, and influences price trends. Disruption might occur due to resources scarcity but also to political instability, geopolitical risks and potential export restrictions of the few countries in which the resources are concentrated (IEA 2022). Based on the above considerations, the following descriptors of energy security are identified: adequacy, reliability and uninterrupted supply of inputs; stability and affordability of prices.
- **Energy resilience** refers to the ability to reduce and withstand the magnitude and/or duration of disruptive effects, which include the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event (EC 2018). Resilience can then be addressed by the following descriptors: redundancy; efficiency; diversity in market, suppliers and technologies; risks reduction; security; adaptive capacity.

- **Energy social sustainability,** according to IEA (2022), involves minimizing greenhouse gas (GHG) emissions to align with net zero targets. It ensures the efficient and responsible use of natural resources, which includes promoting recycling, reusing materials, and managing end-of-life processes in an environmentally friendly manner; and ensuring that Environmental, Social, and Governance (ESG) principles and practices are recognized and implemented throughout the entire value chain. Energy social sustainability entails not only impacts but also opportunities: it is anticipated that new job opportunities will emerge, necessitating a more skilled workforce (IEA 2022). Estimates suggest that by 2030, nearly two-thirds of new workers in the clean energy sector will be highly skilled, with most requiring extensive training, including both upskilling (acquiring new skills) and reskilling (learning new skills for different roles). Also, the European Pillar of Social Rights action plan, which sets targets for 2030, emphasizes the importance of creating more and better jobs, enhancing skills, and promoting equality.

It appears clear that energy security, resilience and sustainability are affected by vulnerabilities in the supply chains, meant as elements with a high chance of significant and widespread disruption, and that affect the capacity of the supply chains to respond and limit the effects of a disruption (IEA 2022). The European Commission addresses these aspects by using an indicator called "supply risk" assessing the risk of inadequate supply of a raw material to industry demand (Blengini et al. 2017). The "supply risk" of raw materials is based on the concentration of primary supply from producing countries and their governance, but also to the actual mix of EU sourcing of raw materials. Trade and import dependency aspects are considered, together with raw materials substitution and recycling as risk reducing measure. In the context of the energy technologies supply chains, IEA (2022) identifies three criteria for measuring vulnerability, together with those for responding and addressing the vulnerability, which are described in Table 2.

Table 2. Criteria for describing vulnerability.

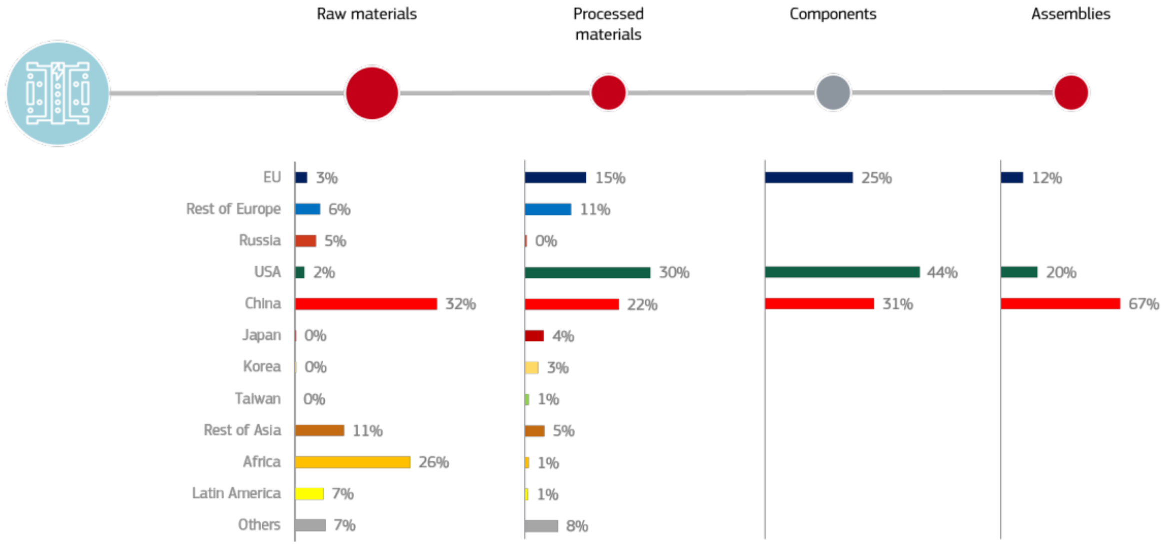
CRITERIA	DESCRIPTION
Elements of disruption	
Supply chain concentration	Highly concentrated production will increase the likelihood of a significant disruption due to increased risk of the entire market being exposed to the same shock. Supply concentration can be expressed in terms of: - Geographic concentration, i.e., the extent to which a production is concentrated in a single geographic area. - Market concentration, i.e., the extent to which a production is concentrated in a single company. - Technology concentration, i.e., the extent to which there is/are a single/few technologies, a situation that might limit the technology transfer.
Pace and scale of growth	A larger scale-up requirement compared to the average pace observed in that market, or the rapid development of a new supply chain to reach net zero, will increase the likelihood of a situation where demand and supply become imbalanced.
Exposure to trade, natural, technological or geopolitical risks	High exposure to potential disruptions, such as trade restrictions, technological disasters, natural disasters, conflict or political instability will increase the likelihood of a disruption, especially when coupled with a highly concentrated market.
Strategies to reduce the impact of supply disruption	
Ability to pivot to other materials or technologies	In the event of a disruption, the impact will be reduced if there are readily available substitutable technologies and materials, and the supply chain can pivot to them with relative ease. Using a range of materials and technologies would reduce the supply chain impact.
Scale-up or conversion lead times	The speed at which a supply chain can reorganize will have significant impact on the extent of the disruption and the supply chain's resilience. The scale-up and conversion times for infrastructure will be a critical element of the reorganization.

Source: IEA (2022)

The need for a diversification of the global suppliers of those critical and strategic raw materials used in the hydrogen value chain is highlighted also by the Hydrogen Europe Position Paper (Hydrogen Europe 2023), while recognizing the unavoidable dependencies for the sourcing of some materials such as Platinum Group Metals (PGMs), which originate mainly from South Africa.

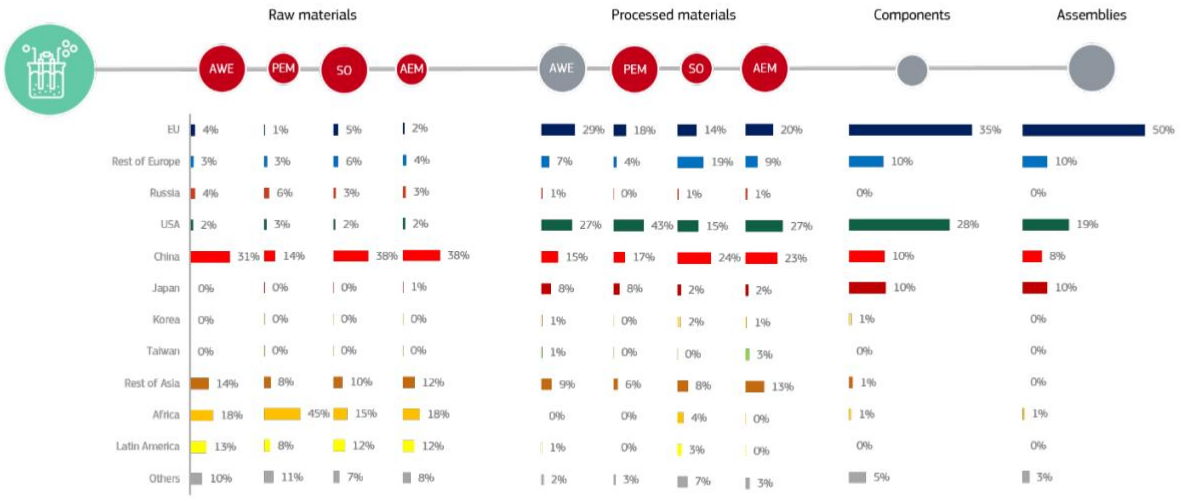
Carrara et al., 2023 provided an overview of supply risks, bottlenecks and key players along the supply chains of fuel cells and electrolysers. For both the technologies, the highest risks are for is the raw material and processing step. Figure 7 and Figure 8 illustrates the supply chain steps and the associated risk. The results of the analysis show that the EU faces significant supply risks in the fuel cell and electrolyser value chains due to reliance on critical raw materials mainly from China and other politically unstable regions, necessitating actions such as supply diversification, improved recycling and substitution strategies, enhanced R&D, and skills development to strengthen manufacturing capacity and preserve innovation, ultimately supporting the transition to green hydrogen and achieving net-zero targets.

Figure 7. An overview of supply risks, bottlenecks, and key players along the supply chain of fuel cells



Source: Carrara et al., 2023

Figure 8. An overview of supply risks, bottlenecks, and key players along the supply chain of electrolysers



Source: Carrara et al., 2023

According to the IEA (2022) report, a medium vulnerability risk for resource extraction, material production and manufacturing/construction has been defined, while a low risk has been identified for the operation stage, as illustrated in Table 3. In addition, Hydrogen Europe pointed out the importance of considering not only critical raw materials but also strategic processed materials such as fluoropolymers (Hydrogen Europe 2023).

Table 3. Assessment of vulnerabilities for hydrogen technologies by supply chains.

	RESOURCE EXTRACTION	MATERIAL PRODUCTION	MANUFACTURING/CONSTRUCTION	OPERATION
Hydrogen	🟡	🟡	🟡	🟢

Yellow: medium
Green: low

Source: IEA (2022)

In the resource extraction step of the hydrogen value chain, the use of critical raw materials such as platinum for hydrogen electrolysers represents a moderate vulnerability, because of the concentrate production of these materials and of their location in areas exposed to social and geopolitical conflicts. The concentration of technologies and processing activities also represent a moderate vulnerability risk, because currently the supply of membranes for electrolysers is being dominated by a few suppliers. However, in the future, the production is likely to become more diversified compared to other technologies such as battery and solar PV.

The need for ensuring the EU's access to a secure, diversified, affordable and sustainable supply of Critical Raw Materials (CRM) is highlighted also in the European Critical Raw Materials Act – CRMA (EC 2024), which has set the upper benchmark of no more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing sourced from a single third country, as criterion to limit the potential risk of supply disruption and increase the EU’s resilience.

4.1.2 Selection of social topics

Building upon the insights from the analysis of social dimension in the policy initiatives on clean energy technologies transition, the social topics listed in Table 4 have been identified, as input for the definition of the conceptual framework. These aspects are relevant for clean energy technologies in general, and for hydrogen in particular.

For each dimension, social topics have been defined, together with potential indicators: some of them are already quite established, while others require a more in-depth investigation for a proper quantification.

Table 4. Social topics relevant to consider for the clean energy technology transition, including hydrogen.

SOCIAL DIMENSION	SOCIAL TOPIC	POTENTIAL INDICATORS
Energy security	Affordability	Different indicators can be defined[6]
	Uninterrupted availability	Exposure to risk (trade, natural, technical, geopolitical)

---

[6] Many indicators have been suggested for measuring affordability. Three main approaches have been identified in literature: fixed threshold of energy expenditure versus income; relative measure where the threshold is set relative to the average expenditure on energy; a residual income approach measures affordability based on the idea that a household must make certain purchases beyond utilities. (Lin 2018). EUROSTAT measures the “Access to affordable energy” with the indicator “Population unable to keep home adequately warm”. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=SDG_7_-_Affordable_and_clean_energy#Affordable_and_clean_energy_in_the_EU:_overview_and_key_trends

SOCIAL DIMENSION	SOCIAL TOPIC	POTENTIAL INDICATORS
Energy resilience	Diversity in market, suppliers and technologies	Supply chain concentration (geographic, market, technologies)
	Risk reduction	Exposure to risk (trade, natural, technical, geopolitical)
	Adaptive capacity	Different indicators can be defined[7].
Energy social sustainability	New jobs	Different indicators are available. See section 5 for details.
	More skilled work (upskilling/reskilling)	This social topic can be accounted for under “new job”, by accounting for the level of knowledge/experience. See section 5 for details.

Source: authors’ elaboration

---

[7] Specific skills and mechanisms that are deployed by human systems to contribute to resilience. Technology is one determinant of adaptive capacity and ,can be measured according to 3 indicators (EEA 2021): R&D expenditure as % of GDP, number of R&D personnel, number of patent application (https://www.eea.europa.eu/data-and-maps/figures/technology-as-one-determinant-of). In addition, the overall concept of adaptive capacity (to climate change is measured by EEA as weighted combination of data on economic, infrastructural, technological and institutional capacity as well as knowledge and awareness of climate change (https://www.eea.europa.eu/data-and-maps/figures/potential-aggregate-impact-adaptive-capacity).

4.2 Characteristics of hydrogen technologies with potential implications on social impacts

In this section, the key distinguishing elements of hydrogen technologies that might have a social counterpart have been identified. They represent both risks and opportunities, and together with the insights from sections 4.1 and from the analysis of the literature on social impacts, they drive the definition of social material topics for hydrogen technologies.

Three types of risk factors have been identified in literature:

- **Risk factors related to the supply chain processes and governance** (Azadnia et al. 2023), covering the following aspects:
    - Risk of a discontinuous resource supply (materials and equipment for hydrogen production), due to geopolitical issues in the countries from where resources are purchased. This risk is common to other clean energy technology supply chains, characterized by the use of critical raw materials (IEA 2022).
    - Supplier failure in delivering critical raw materials and equipment for hydrogen production, an aspect that can disrupt the entire supply chain. Failure can be driven by the lack of available resources to fulfil the demand (capacity constraint) or a technological accident involving hydrogen or other source material.
    - Lack of collaboration and transparency, as it might generate distrust and conflict among actors along the value chain.
- **Risk factor related to health and safety**:
    - Risks for workers related to exposure to hazardous materials, unsafe working conditions, potential accidents during the production, transportation, and storage of hydrogen. Safety and reliability of the required infrastructure is considered a necessary condition for the development and uptake of hydrogen technologies (Moradi and Groth 2019).
    - Risks for the population due to potential accidents during the e.g., handling, transportation or storage of hydrogen (Calabrese et al. 2024).
- **Labour risk** (Azadnia et al. 2023): linked to potential unfair working conditions, which in turn can lead to labor strikes, which will impact production. This risk is not considered strictly inherent to the hydrogen value chain but mainly dependent on the capability of the organization(s) in charge of managing and running the technology to ensure that measures are in place for adequate working conditions.

Opportunities are mainly identified in terms of flexibility and skilled human resources. Regarding flexibility, hydrogen technologies favour decentralized[8] systems, local and individual solutions, which make them suitable also for small and isolated contexts, where other technologies could not be applied (Dincer 2007). From the human resources point of view, the availability of a skilled

---

[8] Decentralized energy systems are characterized by small-scale energy generation units that could be stand-alone or connected to others through a network to share resources (Vezzoli et al. 2018).

workforce is crucial for the hydrogen industry's growth, and it linked to education, training, and job creation, which impact employment opportunities and economic well-being.

4.3 Methodologies and tools for the social assessment of hydrogen and energy technologies

This section presents the main insights from the literature review on the extent to which and how the social dimension of energy technologies and systems, and hydrogen technologies in particular, has been addressed. Based on the criteria for the literature review described in section 3, the results are structured according to two main groups of contributions: approaches based on the life cycle thinking, in which S-LCA has been applied and in some cases also further broadened to include indicators suitable for addressing hydrogen and/or energy technologies; approaches that go beyond the S-LCA and are rooted into technology assessment and/or are fed by sociological approaches.

4.3.1 Life cycle-based methodological approaches

Among the life cycle-based methodologies for social assessment, the Social Life Cycle Assessment (S-LCA) stand out as a methodology to be considered for the application within the framework. An overview of its main characteristics, opportunities and potential limitations is provided in the next section.

The results of the literature review can be clustered in two main groups:

- Approaches aiming at testing the S-LCA methodology and related S-LCA databases for evaluating the impact of technologies, without questioning the suitability of the methodology. Within this group, there are also contributions aimed at identifying suitable social topics, relevant for energy technology in general, and for hydrogen technology specifically, with a focus on social aspects of critical raw materials in the supply chain.
- Approaches aimed at defining a framework for the social and/or sustainability assessment of technologies, including novel technologies.

4.3.1.1 Social Life Cycle Assessment

S-LCA aims to assess positive and negative social impacts, performances and risks of products along their life cycle, with the ultimate goal of improving human dignity and wellbeing (UNEP 2020). The development of the methodology has been put forward by two main initiatives, namely:

- The Social LC Alliance, under the umbrella of the UN Life Cycle Initiative. The Alliance is a network of experts from enterprises, social organizations and institutes, academia and consultants, with the ultimate goal of sharing knowledge and experience about the S-LCA methodology. The Alliance has promoted and contributed to the delivery of two reference documents: i) the Guidelines for Social Life Cycle Assessment (UNEP 2020), which provide guidance on the main methodological aspects when dealing with S-LCA; ii) the Methodological Sheets for Subcategories in Social Life Cycle Assessment (UNEP 2021), which provide references to social topics and related indicators and data sources on all the social topics addressed by the Guidelines, and for all the stakeholders’ categories in scope (workers, local communities, value chain actors, consumers, society, and children).

- The Handbook for Product Social Impact Assessment (Goedkoop et al. 2020), which promotes a qualitative approach for the evaluation of social impacts, and it is built upon the capital approach (e.g., Social & Human Capital Coalition 2018).

These guidelines and handbook are still the main methodological references for the S-LCA, complemented by the following initiatives:

- The work carried out within the ORIENTING Project[9], in which the development of the S-LCA has been put forward, focusing on making the S-LCA methodology operational (ORIENTING 2023; ORIENTING 2024).
- The S-LCA and Life Cycle Sustainability Assessment (LCSA guidelines for hydrogen energy systems developed in the framework of the SH2E Project[10]).

In parallel, a standardization process of the methodology has started, under the TC 207/SC 5, which has delivered the standard ISO 14075 Environmental management Principles and framework for social life cycle assessment.

General features of the S-LCA

The S-LCA methodology is characterized by the following distinguishing elements:

- It is based on the life cycle thinking, i.e., social aspects are considered along the whole life cycle, from raw material extraction until the end of life.
- It mirrors the LCA structure and its main principles, with some exceptions[11].
- It is focused on product level, where a product includes also services and technologies.
- It is built upon the concept of stakeholders, i.e., group of people that can be affected by or affect the activities of organizations involved in the life cycle of the product.

According to the S-LCA methodology, social risks, performance and impacts can be assessed:

- Social risk: the likelihood and magnitude of negative effects that may be avoided through preventive actions.
- Social performance: it refers to "the principles, practices, and outcomes of businesses' relationships with people, organizations, institutions, communities, and societies in terms of the deliberate actions of businesses toward these stakeholders as well as the unintended externalities of business activity measured against a known standard" (UNEP 2020).
- Social impact: consequences of positive or negative pressures on social areas of protection, often defined as human dignity and well-being of stakeholders (Pikhola et al. 2023).

---

[9] Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy. www.orienting.eu

[10] SH2E - Sustainability Assessment of Harmonized Hydrogen Energy Systems: Guidelines for Life Cycle Sustainability Assessment and Prospective Benchmarking. https://sh2e.eu/. The guidelines have been published in May 2024 and are available for download at https://sh2e.eu/downloads/

[11] A clear exception is the linearity principle, which is not applicable to S-LCA. According to it, the double the quantities in the inventory, the double the impact. However, social impacts are sensitive to threshold and the quantities do not always matter: 2 units of child labor within an organization are a concern like 1 unit.

Social topic and social impacts in S-LCA

Often the term *social topic* is used to indicate an issue of concern from the social perspective and include both performances and risks (ORIENTING 2023)[12]. Impacts, performance and risks are assessed in relation to stakeholders, defined as a group of people that can be affected positively and negatively by the activities of organizations involved in the life cycle of the product under consideration and include workers, local community, users/consumers, small scale entrepreneurs, value chain actors, society and children. The social topics are linked to stakeholders: the same social topic might be relevant for more than one stakeholder. The relation between them is described in Annex 1 with reference to the list of social topics defined in ORIENTING project.

While product is the central focus of the S-LCA, social impacts are the results of actions undertaken by stakeholders affected by activities in the value chain in which the product is designed, manufactured, used and managed at the end of life. Thus, in most of the cases what is measured and evaluated is the extent to which organizations running the product system under analysis have implemented measures to mitigate a potential risk or to avoid a potential social impact. Even for the stakeholder “Society” social impacts are assessed in terms of degree of engagement of the company in social issues: e.g., for the social topic “Corruption” what is measured are measures put in place by an organization to prevent corruption. In macro-scale analysis of value chains (e.g. Martin Gamboa et al. 2024), the focus is mainly on assessing risk at country-sector level, identifying potential social hotspots from sourcing countries in alternative value chains.

S-LCA has some limitations in assessing emerging technologies. Indeed, when the object of the analysis is a technology, not yet available on the market, there is not an organization whose behaviour can be evaluated. In addition, new technologies might create large scale effects, occurring in the future, and pose also a question of acceptability by stakeholders, which varies according to the contexts.

Current S-LCA methodology is not able to account for these requirements, and thus it is not ready-to-use for the application to hydrogen technologies but requires to be further developed and adapted, because the overarching perspective applied in S-LCA, namely the one of the organization, is not applicable. A perspective that considers how the development of a technology would affect the social structure in which it will be embedded is lacking (Zamagni, Amerighi, and Buttol 2011), while it should be part of any social impact assessment of technologies. In addition, social topics and indicators shall be technology-specific, i.e., be able to capture inherent characteristics of technologies that might create social impacts. For example, small-scale production makes the technology more distributed, thus easing its access also to remote areas and contributing to the rural development.

---

[12] ORIENTING - Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy – is a project funded under the European Union’s Horizon 2020 Framework Programme. Concluded in 2024, it developed a toolbox for operationalising Life Cycle Sustainability Assessment (LCSA). The toolbox consists of LCSA methodology, an entry level template to provide guidance for users towards a preliminary identification and understanding of potentially relevant sustainability topics and impacts in the product life cycle, an LCSA integration tool and training materials. More information is available at https://orienting.eu/

4.3.1.2 *Identification of social indicators for energy and hydrogen technologies*

The analysis of the literature pointed out that there is no consensus on the use of indicators for the social assessment of hydrogen system, and that, in many cases, the rationale underpinning the choice of the proposed indicators is not sufficiently explained. Reference is made to the link of these social topics with the UN Agenda 2030 Sustainable Development Goals, as well as to the specific goal of the projects in whose framework the social assessment was conducted. Thus, the materiality approach followed remain unclear. In addition, the following main trends have been identified among the published studies that adopt a life cycle-based approach:

- there is a polarization of approaches around a few research groups, which are aligned in terms of social topics and indicators identified, and cover mainly the stakeholders' category workers, society, value chain actors and local community.
- When specific approaches for assessing hydrogen technologies are presented, such as the Social LCA guidelines developed in the framework of the SH2E Project[13] (Iribarren et al. 2023), recommendations on the indicators for fuel cell and hydrogen systems are not provided, due to the variability in technologies, supply chain, sectors and products included in the hydrogen value chain.
- The indicators used in the analysed studies are usually those also used in the PSILCA database and suggested by the Methodological Sheets for S-LCA (UNEP 2021). New social topics and related indicators, compared to the existing ones included in S-LCA databases and Methodological sheets, have been proposed by a few authors. These include:
    - Acceptance, which is expressed in terms of yes/no and accompanying rationale. In all the analysed approaches, surveys were carried out, with dedicated questions, and results have a context-specific validity.
    - Technology innovation, measured in terms of patents, using different indicators.
    - Security and diversity of supply, described in terms of depletion of fossil fuel reserves; import dependency; availability of renewable energy resources; reliability of supply.
    - Intergenerational issues, described by mitigation of climate change and depletion of fossil fuel reserves, with the use of Global Warming Potential and Abiotic Depletion Potential indicators used in Life Cycle Assessment methodology.
    - Large accident risk, as part of health and safety impacts (the social topic has been proposed in the context of the assessment of nuclear energy technologies)
- Most of the identified social topics and indicators can be evaluated in terms of social risks, and thus as likelihood of occurrence, according to a social risk assessment approach. They are calculated by combining the social profile of the country/sectors involved in the supply chain and the number of working hours to produce the analysed product (Valente, Iribarren, and Dufour 2019).

---

[13] Sustainability Assessment of Harmonised Hydrogen Energy Systems: Guidelines for Life Cycle Sustainability Assessment and Prospective Benchmarking. https://sh2e.eu/project/

- There is no consensus in the scientific community on the use of “worker hours” as an activity variable[14] to perform social LCA studies: some authors (e.g., Ciroth et al., 2019 have pointed out that it is questionable, because there are indicators that are not linked to the worker hours used in a process, while others (Campos-Carriedo et al., 2024) have highlighted the relevance of the approach. Being the activity variable an arbitrary choice for scaling social risks and performances to the processes, it is recommended to interpret with caution the results obtained when drawing conclusions.

Most of the approaches analysed in literature have used PSILCA (Product Social Impact Life Cycle Assessment) as background database for either covering the remote parts of the value chain on which data were not available, and for running the assessment. S-LCA databases use public data sources for a set of social topics and indicators and provide a risk assessment scheme where the values of the indicators are associated to specific risk levels (Di Noi et al. 2020). The databases enable the analysis of the potential social risk of supply chains of raw materials industries in the EU. These risk-based indicators only partially account for the peculiarities of the technology they are describing but reflect mainly the sector/country performance in which the value chain of the analysed technology is embedded.

Many of the social risks are context specific, and require to be evaluated locally, and thus cannot be generalised neither at country nor at sector level. However, when the information about the technology is limited either because it is at the initial stage of development (low TRL) or because the structure of the supply chain is not fully known, they provide a first understanding on whether and where social hotspots might occur. In these circumstances, social databases allow the identification of potential risks to be taken into account according to a precautionary approach, and allow defining preventive actions for mitigating these risks.

4.3.1.3 Social impacts in the hydrogen supply chain

Studies investigating the supply chain from the social point of view reveal that major social hotspots can occur, due to the manufacturing of the equipment for hydrogen production (Akhtar et al. 2023). When the equipment is manufactured in Europe, a notable decrease in most of the social indicators can be seen, as confirmed also by IEA (2022). In particular, the platinum used for the stack manufacturing is a clear social hotspot, and in general manufacturing processes for materials are found to have higher social risks than manufacturing processes for components (Bargiacchi et al. 2022), (Mori et al. 2023), (Schlör et al. 2017).

Upstream processes in the supply chain, which include mining and quarrying, contribute more than 90% to most of the social topics, and significant impacts of different raw materials originate in extra-EU countries, with the highest risks associated with the social topics “corruption”, “fair salary”, “freedom of association and collective bargaining”, and “health and safety” (Mancini et al. 2018); (Di Noi et al. 2020). A recent study compares two prospective value chains for hydrogen use in EU: an on-site option, where hydrogen is produced and used in the same European country, and an off-site option, where hydrogen is produced in a European country different from its usage. Results show that the off-site value chain has a worse social performance (6-72 times than the on-site option across most selected indicators. Moreover, in both value chain configurations, the potential risk of

---

[14] Activity variables, like” worker hours”, are parameters used to reflect the share of a given activity associated with each unit process (UNEP 2020).

child labour is concentrated mainly in the component manufacture stage (Martín-Gamboa et al. 2024).

The prospective value chains of the study of Martín-Gamboa et al. (2024) have been designed based on a protocol for the identification of supply chains of novel technologies (Martín-Gamboa et al. 2020; Martín-Gamboa, Dias, and Iribarren 2022). This approach allows for defining in a practical way the system boundaries of a S-LCA study, by identifying the relevant unit processes to be accounted for. The protocol combines trade data and LCI databases for identifying the unit processes of the technology involved and their location. First, raw materials, components and energy flows are identified, together with their countries of origin and the country where the technology is manufactured. Economic data related to exports and imports are used, retrieved from UN Comtrade Database, for identifying the country of origin for components (one country only and materials (more than one is possible).

Overall, the literature pointed out the usefulness of S-LCA databases to compensate the limited data availability that might occur e.g., along the supply chain or when new technologies are evaluated (Hake et al. 2017); (Schlor et al. 2017); (Iribarren and Dufour 2018); (Valente, Iribarren, and Dufour 2019); (Werker, Wulf, and Zapp 2019); (Di Noi et al. 2020); (Martín-Gamboa et al. 2020); (Muller et al. 2021); (Valente, Iribarren, and Dufour 2021); (Wulf and Zapp 2021); (Bargiacchi et al. 2022); (Martín-Gamboa, Dias, and Iribarren 2022); (Akhtar et al. 2023); (Mori et al. 2023). It is however suggested to complement the outcomes of these database-driven assessments with additional literature analysis, to make the results more fit for purpose and adhering to the specific context of the application (Wulf and Zapp 2021).

4.3.1.4 Frameworks for the social and/or sustainability assessment of novel energy technologies

When the object of the assessment is a novel technology, the S-LCA framework has been perceived as too narrow by some scholars, who have proposed:

- A forward-looking perspective to account for social impacts related to technologies not yet available on the market.
- Adoption of a macro level perspective, thus accounting for key social drivers and goals in the energy policy, such as energy justice and autonomy (van Haaster et al. 2017).

In addition, a framework for assessing the social impacts from large scale implementation of novel technologies, based on S-LCA, has been proposed by (van Haaster et al. 2017). The **macro-level perspective** adopted by van Haaster aims at capturing the interactions between the technology and the society, based on the following building blocks:

- use of input-output model.
- adoption of a relative approach, i.e., novel technologies are considered to replace a technology with similar functions.

- identification of four areas of concern[15] for social well-being, the area of protection in S-LCA, namely: autonomy, safety, security and tranquillity (it includes also issues such as satisfaction); equality (level of disparity among countries); participation and influence. For each area of concern, social indicators have been defined, both quantitative and qualitative, reported in Table 5.

---

[15] An area of concern is a topic defined by the interest of society (Ridoutt et al. 2016)

Table 5. Area of concern and related indicators for the assessment of large-scale impacts of novel technologies suggested by van Haaster et al. (2017).

Area of concern	Social indicator	Definition	Type of indicator
Autonomy (Defined as being in control of oneself and one's resources, autonomy is negatively impacted by for example, forced labour or slavery.)	Child labour	Work that deprives children of their childhood, their potential and their dignity, and that is harmful to physical and mental development (ILO 2013). It concerns hazardous work done by children and other severe forms of child labor.	Quantitative
	Forced labor	Work or service which is exacted from any person under the menace of any penalty and for which the said person has not offered himself voluntarily.	Quantitative
Safety, security and tranquillity It is a combination of freedom from threats to human health and property. It also includes aspects related to the beneficial impact of employment (which goes beyond receiving a salary but also include issues such as satisfaction).	Knowledge-intensive jobs	High-skilled employment. Includes workers as managers, professionals, technicians and associate professionals for which education is required.	Quantitative
	Total employment	Share of the labor force—the total part of society that is available for work—that is working.	Quantitative
	Possibility of misuse	Potential use of the technology that causes harm to people or society. The vulnerability of the novel technology to be used in hazardous ways such as sabotage or terrorism.	Qualitative
	Risk perception	Observation of hazard by the general public. The perception of risk can cause instability because of decreasing overall feeling of safety in a society.	Qualitative
Equality It represents the level of disparity among countries and/or regions. Equality is for example negatively impacted by increasing disparity in income distribution.	Income inequalities (GINI coefficient)	Structural disparities between salary levels, representing a gap between rich and poor. The indicator regards the degree to which global income inequalities are affected by the introduction of the novel technology.	Quantitative
	Regional inequalities (€)	Disparities between GDP levels around the world, comparing the GDP levels of developing countries with those of developed countries.	Quantitative
Participation and influence Defined as 'the act of taking part or sharing in something and affecting the course of event' (Farlex Inc 2012). It includes the level of participation in decision-making processes.	Trust in risk information	Confidence of being informed in case of hazard. The indicator regards the degree to which the general public feels confidence that they will be informed in case of hazard.	Qualitative
	Stakeholder involvement	Active participation of interested parties within decision-making processes. The indicator regards the degree to which the interested parties are involved within decision-making processes concerning the novel technology.	Qualitative
	Long-term control functions	Governance or technical instruments such as regulating authorities or redundant systems that ensure long-term control will. The indicator regards the degree to which people trust that the technology is adequately controlled.	Qualitative

Source: van Haaster et al. 2017

Some of these social indicators such as risk perception are relevant for technologies where chemical hazards occur, such as hydrogen..

The macro-scale is considered also when the concept of **energy justice** is proposed to be included within the S-LCA framework. The proposal of Fortier et al. (2019) mainly focuses on introducing indicators for measuring energy justice for electrical energy systems within the current S-LCA framework. Indicators have been defined for four categories of stakeholders, namely workers, local communities, electricity consumers, society, which capture the following aspects:

- for electricity consumers: potential impacts related to costs and affordability of electricity generation.
- for local community: the potential different burdens of different groups due to their proximity to electricity generation sources or industrial sites and their associated pollution.
- For workers: potential health and safety and labour conditions.
- For society: potential impacts due to accessibility of R&D results, contribution to economic progress, engagement in the promotion of low carbon energy systems.

According to the framework, it is possible to evaluate energy systems that have the overarching goal to minimize the injustice along the whole life cycle, while the applicability at the level of single technology is considered less meaningful. Considering the types of indicators, the applicability of the framework is limited to technologies already on the market, for which specific data on current performances can be collected, even if the use of background social databases might support the quantification of some of the indicators. In addition, the whole set of area of concerns are needed for evaluating energy justice, while the cherry-picking and/or individual use of indicators is not recommended, due to the dependencies among them: even if it is difficult to capture them quantitatively, their comprehensive interpretation is crucial for an overall evaluation of the technology system.

S-LCA has also been combined with the **capability approach** of Amartya Sen (Schlor et al. 2017). The capabilities focus on the quality of life that people can actually achieve. This quality of life is analysed in terms of the central concepts of “functioning” and “capability”. This theoretical framework involves two normative claims. First, the assumption that freedom to achieve well-being is of primary moral importance. And second, that freedom to achieve well-being must be understood in terms of people with capabilities (Thomas R. Wells 2012). The capability approach is applied to capture the social conditions of hydrogen production, i.e., quantify relations between production patterns and social conditions, as analysis of the human well-being along the hydrogen production chain. Five main functions of the capability approach have been selected, and for each, social topics from the Social Hotspot Database and indicators have been selected and defined (Table 6):

Table 6. Social topics and indicators of the combined S-LCA and capability approach by Schlor et al. (2017).

Functioning of the capability approach	Social topic	Indicators
Welfare basis	Labour rights	Risk of forced labor
		Risk of average wage below minimum wage
		No adequate labor laws
		Commercial labor
		Risk of workplace noise
		Migrant workers treated unfairly
		Wage under 2 dollar per day
		Excessive working time
		Unemployment
Social participation	Human rights	Risk of child labor
		Risk of gender inequality
		Indigenous population
Democracy and freedom	Governance	Overall risk of corruption
		Fragility of the legal system
Health and safety	Health and safety	Risk of fatal injuries
		Risk of low life expectancy
		Mortality from communicable diseases
		No access to improved drinking water
		No access to improved sanitation
Decent life	Community infrastructure	Children do not attend school
		Risk too few hospital beds

Source: authors' elaboration

In contrast to other approaches, the proposal of Schlor et al. (2017) enriches the S-LCA perspective, attempts to define epistemological foundations of the methodology in the context of the social sciences. This understanding of the methodological foundation can help guide the selection of stakeholders and indicators to be measured, but limited research has been done so far.

Indeed, it has been pointed out that S-LCA should adopt a sociological perspective according to which the subject of the assessment are not the actors themselves, but the relations between them (Soltanpour, Peri, and Temri 2019). According to this view, the social topics covered in S-LCA should go beyond human rights and respect of minimum standards, and target conditions that effects not just some individuals but entire generations. Soltanpour, Peri, and Temri (2019) suggest that S-LCA “covers the social interactions that have been changed due to a change in the product system and discuss to what degree the change would create social disorder (or order)”. In terms of practical implications, issues such as inequality, democracy and social exclusion, are those relevant to be evaluated.

It can be concluded from these works that the scope of a social assessment should entail the whole energy/technology system, and not the single technology, or at least not for all the social topics. In fact, at the macro level the impact of a single technology could potentially be large, depending on the level of penetration and its role for society (van Haaster et al. 2017). However, the need for explicating the underpinning epistemological foundation remains, to clarify not only what kind of questions can be answered and the intended uses supported by the framework, but also to define indicators and methods for its implementation.

4.3.2 Technology Assessment and other approaches

Beyond the S-LCA methodology, there are plenty of approaches for dealing with the social impact of energy technologies, either as a stand-alone or within the framework of a sustainability assessment. They differ in the technological scope (hydrogen vs energy technologies), in their nature (procedural guidance vs quantitative-semi-quantitative vs qualitative approaches) and in the identified social criteria and indicators used for measuring the impacts and risks. In addition, not all of them account for a life cycle perspective but focuses on specific social aspects, such as acceptance, analysed from the perspective of a few stakeholders (e.g., local population).

Approaches have been identified aimed at developing conceptual framework for the assessment/evaluation of social sustainability in general or focused on specific aspects such as social justice (Eizenberg and Jabareen 2017), (Carbajo and Cabeza 2019). They include contributions that provide insight on ontological and epistemological foundations of social sustainability. Equity (or Justice), risk/safety (the rights to be protected and secured in situations of vulnerability) and Urban Forms have been highlighted as the ontological foundations of social sustainability (Eizenberg and Jabareen 2017) among others. Risk as ontological foundation of a social assessment becomes clear and relevant when considering the assessment of hydrogen and clean energy technologies, because the energy transition has consequences in terms of the distribution of benefits and risks on citizens and society.

Equity is a concept that is introduced within several studies. For example, distribution of benefit is a dimension of equity (redistributive), referring to ensuring people rights, such as the right to energy, the right to adequate standards of living, and the right to clean air, water, and related resources. Other dimensions of equity are represented by recognition, i.e., recognition of the voice of the disadvantaged and the vulnerable, and participation, i.e., involvement of and interaction among people (Eizenberg and Jabareen 2017).

Urban Form refers to the physical dimension of the community, that should “promote a sense of community, safety, health, and place attachment” (Eizenberg and Jabareen 2017). These are guiding concepts to the definition of any conceptual framework of hydrogen technologies, aiming at going beyond a common practice of defining frameworks as an assembly of indicators frequently not grounded in theory but based on their plausibility of applicability and relevance for hydrogen and energy technologies, and occurrence in literature. In fact, the overarching theoretical construct is in a few cases defined (e.g., (Eizenberg and Jabareen 2017); (Grafakos, Enseñado, and Flamos 2017); (Carbajo and Cabeza 2019), but in many other it is not clearly outlined.

The methodological approach proposed by the **SAT (Sustainability Assessment of Technologies) framework** (UNEP 2012) focuses on the process for conducting a sustainability assessment and on the role played by stakeholders. Conceived for being applied at the level of technology system, and no single technologies, the distinguishing characteristic of SAT is its tier approach, i.e., the definition of three different levels for performing the sustainability assessment, according to the intended goal and scope. The three levels entail a screening, scoping and detailed assessment in which quantitative procedures are used, combined with sensitivity and scenario analysis. Stakeholders play a relevant role in the SAT, both as users of the methodology and contributor to the evaluation process through their engagement in several consultation processes. This process is thus designed to increase acceptance of stakeholders, being acceptance a key factor of success for the development and installation of new technologies.

There is abundance of literature on acceptance of technologies and/or energy systems, and the literature review carried out in the framework of this assignment did not aim to be comprehensive in this regard but to understand how acceptance is addressed and its main drivers. The main outcomes of this analysis are described later, as part of the analysis of the social topics emerged from the literature.

Regarding the scope, most of the approaches are conceived to assess the social and/or sustainability impacts of energy systems, energy strategies and policies, in some cases also with a specific focus on hydrogen technologies (Gnanapragasam, Reddy, and Rosen 2010); (Acar, Beskese, and Temur 2022); (Haase et al. 2022); Schlor et al. 2022; (Blohm and Dettner 2023). An overview of the addressed social topics and related indicators is provided in Table 7. In the table social topics are defined at two levels: level 1 represents the overarching social topic (or areas of concern), which can be described more specifically by the social topics of level 2.

Table 7. Social topics identified in the literature. The classification in level 1 and level 2 was not present in the original articles and has been introduced for highlighting potential interlinkages and dependencies among the social topics.

Reference	Social topic – level 1	Social topic – level 2	Indicators
(UNEP 2012)	Adaptability to future situations[16]		Several qualitative and semi-quantitative indicators, that address not only the social dimension.
	Environment, health and safety risks	Health and safety risks	Risk levels for workers Risk level for communities/beneficiaries
	Acceptability		
	Income generation potential		
(Blohm and Dettner 2023)	Energy poverty		Construction of additional power generation capacity in areas where the electrification rate of the local population is below 100%.
	Human rights		Indicators will address the measurement/evaluation of: prohibition of all forms of forced labor, slavery, child labor, discrimination and inequality
	Financial participation		Landowners must be adequately compensated for the use of their land. Regional actors must be given the chance to financially participate in the planned projects
	Employment and added value		Jobs must be created for the local population. Once the technology is introduced, the majority of employees should be local workers. Regional companies must be involved in the economic activities of development, construction and operation & maintenance. The hydrogen should be processed as close as possible to the production site or within the region, if hydrogen derivatives are needed

---

[16] It describes technology system's flexibility or adaptability to future scenarios. This includes the possibility of e.g., scaling-up, expanding or upgrading the technology to meet changing needs.

Reference	Social topic – level 1	Social topic – level 2	Indicators
	Technology and knowledge transfer *(only relevant to consider in countries which lack the necessary knowledge in the field of planning, construction or operation and maintenance of renewable technologies or hydrogen production facilities)*		Business models and adequate training (practical and academic of the civil society for emerging jobs must be provided by involved project partners. Capacity building and training for new skill requirements must be integrated in the technology transfer. Capacity building for decision-makers must be offered by international project partners, if needed
Hirschberg et al. (2008); Carrera and Mack (2010)	Continuity of energy service over time (security/reliability of energy provision)	Political threats to continuity of energy service	Diversity of primary energy suppliers: Market concentration in the primary energy supply (Ordinal scale, expert judgment) Waste management: Probability that waste storage management will not be available (Ordinal scale, expert judgment)
		Flexibility and adaptation	Flexibility to incorporate technological change (Ordinal scale, expert judgment)
	Political stability and legitimacy	Potential of conflicts induced by energy system	Potential of energy system induced conflicts (Ordinal scale, expert judgment)
		Willingness to act (mobilization potential)	Willingness of NGOs and other citizen movements to act against the realization of an option (Ordinal scale, expert judgment)
		Necessity of participative decision-making processes	Necessity of participative decision-making processes for different technologies (Ordinal scale, expert judgment)
	Social and individual risks	Expert-based risk estimates for normal operation	“Reduced life expectancy due to normal operation”: Mortality due to normal operation (YOLL[17]/kWh) Non-fatal illness due to normal operation”: Morbidity due to normal operation (DALY[18]/kWh)

---

[17] Years of life lost

[18] Disability affected life years.

Reference	Social topic – level 1	Social topic – level 2	Indicators
		Expert-based risk estimates for accidents	Expected health effects from accidents: Expected mortality due to severe accidents (Fatalities/kWh)[19] Maximum consequences of accidents: Maximum credible number of fatalities per accident (Fatalities/accident)
		Perceived risk	Perceived risk characteristics for normal operation: Subjectively expected health consequences of normal operation (Ordinal scale, expert judgment) Perceived risk characteristics for accidents: Psychometric variables such as personal control, catastrophic potential, perceived equity, familiarity (Ordinal scale, expert judgment)
		Terrorist threat	Potential of attack: Potential for a successful attack (Ordinal scale, expert judgment) Likely potential effects of a successful attack: Expected number of fatalities (Ordinal scale, expert judgment)
	Quality of life	Socially compatible development	Equitable life conditions: Share of the effective electricity costs in the budget of social welfare recipient (%) Work quality: Work qualifications expressed as average years of education for workforce (Ordinal scale)
		Effects on the quality of landscape and residential area	Effects on the quality of landscape: Functional and aesthetic impact of energy infrastructure on landscape (Ordinal scale, expert judgment) Noise exposure: Extent to which residents feel highly affected by noise (Ordinal scale, expert judgment) Contribution to traffic: Total traffic load (km/kWh)
Abu-Rayash and Dincer (2019)		Job creation	Not documented

---

[19] The indicator is based on the number of fatalities expected for each kWh of electricity that occur in severe accidents with 5 or more deaths per accident for a particular electricity generation technology chain. The evaluation will be based on historical experience of accidents and on Probabilistic Safety Assessment (PSA).

Reference	Social topic – level 1	Social topic – level 2	Indicators
	Social acceptance		Not documented
		Public awareness	Not documented
		Human health	Not documented
		Human welfare	Not documented
	Social costs		Not documented
(Afgan and Carvalho 2004)		New jobs	Nr of paid hours per kWh produced in lifetime (hours/kWh)
		Capital	The amount of capital of kWh produced in lifetime (USD/kWh)
		Diversity and vitality	Nr of respective entity per kWh produced in lifetime (nr/kWh)
(Buchmayr et al. 2021; 2022)		Landscape quality	Assessment to be based on case study data
		Quality of residential life	No clear cause-effect chain established yet; assessment to be based on case study data (rating of perceived impact on quality of residential life).
		Responsible supply chain with regard to human rights	Risk of contributing to human right infractions and conflicts: relative share of problematic materials along the supply chain
		Responsible supply chain with regard to labor conditions	Risk of contributing to adverse labor conditions
		Human health and safety quality (of the population)	Disability Adjusted Life Years (DALYs), as implemented in ReCiPe
		Job creation	Nr jobs created per MW installed power
		Resource supply risk (in the paper classified as economic impact)	Share of materials with high geopolitical risk of disruption using the GeoPolRisk indicator.
		Energy supply reliability (in the paper classified as economic impact)	Qualitative description of the ability to respond to demand based on technology studies and expert opinions.
(Grafakos, Enseñado, and Flamos 2017)	Resilience	Level of public resistance/opposition	The higher the public opposition, the higher the participatory requirement is

Reference	Social topic – level 1	Social topic – level 2	Indicators
		Aesthetic/functional impact	
		Mortality and morbidity (due to air pollution caused by normal operation of the technology)	
		Accident fatalities	Lost of lives of workers and public during installation and operation
(Acar, Beskese, and Temur 2022)		Impact on public health	
		Employment opportunities	
		Training opportunities	
	Public acceptance		
(Haase et al. 2022)		Innovation	Patent growth rate related to a specific technology
		Public welfare	Domestic value added related to a specific technology
		Public perception	Acceptance of a specific energy technology
(Gnanapragasam, Reddy, and Rosen 2010)	Economic and financial benefits		1: there is a maximum net economic benefit derived from the final product (hydrogen) 0: there is a net economic loss from transforming solid fuels to hydrogen.
	Policy		1: policies and implementation strategies support the sustainability of an element or process 0: policies and implementation strategies act as hindrances.
	Human resources		1: more human work is involved, resulting in job creation and economic benefit for society 0: no direct human work is involved
	Public opinion		1: the majority of the population have a positive opinion 0: there is a negative opinion
	Living standards		1: an element or process within the system improves human living standards indirectly

Reference	Social topic – level 1	Social topic – level 2	Indicators
			0: an element or process does not improve basic living standards
	Human convenience		1: an element or process within the system helps in providing human comforts 0: an element or process does not provide human comfort, through additional hydrogen production.
	Future developments		1: using the element or process increases the possibility for societal development 0: using the element or process within the proposed system does not provide such opportunities, even in the local community
	Lobbying		1: the process or element has effective lobbying 0: no lobbying is attempted
(Heras and Martín 2020)	Social equity		Unemployment rate
			Population density
			Region gross product

Source: authors' elaboration.

4.3.2.1 Additional relevant social topics at macro-scale level

Considering the macro level, the explored literature addresses additional social topics. These consider overarching goals and objectives of energy policies, such as resilience (Grafakos, Enseñado, and Flamos 2017) energy poverty (Blohm and Dettner 2023) and energy justice.

Energy justice describes a system that disseminate benefits and costs of energy service in a fair way, and that has representative and impartial energy decision-making (Sovacool et al. 2017). Besides the social LCA indicators to address energy justice proposed by (Fortier et al. 2019), a conceptual framework for energy justice is provided by Sovacool et al. (2017), according to which energy justice is expressed in function of principles such as availability, affordability, inter and intragenerational equity, responsibility and transparency, among others. While hydrogen economy is considered to support a more just transition (Dillman and Heinonen 2022), potential injustices have been identified, namely risk of accidents, occupation health risks, job losses in competing sectors, risk of technology (know-how concentration, and job losses for vulnerable groups (Dillman and Heinonen 2022).

Other social topics emerging from literature consider the **satisfaction of needs and benefits for society** at large, by accounting for:

- security and reliability of the service provided by the technology (Hirschberg et al. 2008); (Carrera and Mack 2010); (Buchmayr et al. 2021; 2022),
- improvement of human living standards, and economic and financial benefits in general (Gnanapragasam et al. 2010), including also employment creation (Afgan and Carvalho 2004); (Abu-Rayash and Dincer 2019); (Buchmayr et al. 2021; 2022); (Blohm and Dettner 2023);
- human health and safety (Abu-Rayash and Dincer 2019); (Buchmayr et al. 2021; 2022)
- human rights (Buchmayr et al. 2021; 2022); (Blohm and Dettner 2023).

The creation of **economic and financial benefits** is usually described in terms of job creation, which can be measured as e.g., jobs created per MW installed power/kg hydrogen produced. In addition to the number of jobs, also their quality has been proposed as criterion to be considered for a more comprehensive assessment of the potential social impacts. The European Job Quality Index has been proposed, an aggregated index at country level that assesses jobs on six dimensions, namely: Income quality, forms of employment and job security, working time and work-life balance, working conditions, skills and career development, collective interest representation and voice (Piasna 2023).

To overcome the limitation of this indicator in not addressing the impact of different job profiles, a measure of the working conditions quality has been proposed by (Buchmayr et al. 2022). It consists of the absolute number of jobs created and working condition quality criteria based on the OECD job quality framework: The indicator combines information on type of employment (temporary and stable employment, expressed as employment factor – jobs/MW and job profile, the latter expressed in function of salary (as indicator of earning quality, EUR/year gross annual income), education level (assessed with reference to the European Qualifications Framework), occupational risk (as indicator of quality of the working environment, and the ration of temporary to stable jobs (as indicator for labor market security). This proposal is of particular interest because if the number of jobs created is potentially a positive indicator of an economic development, they might not be adequate enough for a decent living, which entails also satisfaction and work-life balance, among others.

Social/public acceptance is addressed almost by all the authors, either as a stand-alone social topic, or as criterion for measuring e.g. resilience, together with others (Grafakos, Enseñado, and Flamos 2017). Acceptance reflects the public's response to technologies, and it is strongly affected by location. There are several studies on acceptance for hydrogen technologies, addressing mainly the use of these technologies in private vehicles and public bus transport (Carr-Cornish et al. 2019); (Schönauer and Glanz 2022). They highlight a neutral or positive response for hydrogen technologies (Haase et al. 2022); (Schönauer and Glanz 2022), and where negative aspects were raised, these were linked mainly to perceived costs rather than to potential risks (Schönauer and Glanz 2022).

However, only a few acceptance studies have considered implementations on a large scale (which entails new infrastructure and changes to the existing system), method of producing hydrogen and hydrogen pipelines, and in those cases, the perception of risk on safety was pointed out (Haase et al. 2022); (Vallejos-Romero et al. 2023). The NIMBY (Not In My Back Yard effect has been pointed out as a key determinant of acceptance, e.g., skepticism about hydrogen storage near or in residential areas has been reported, despite the trust in the storing technology (Carr-Cornish et al. 2019). However, in addition to proximity, socio-demographic factors (Schönauer and Glanz 2022), culture and knowledge of the population, together with the perceived risks and benefits of the technology itself (Emodi et al. 2021), are important aspects that explain the gap between a positive attitude towards the technology itself, and a lack of acceptance or a rejection of the related infrastructure (Carr-Cornish et al. 2019); (Schönauer and Glanz 2022).

In addition to these descriptors of acceptance, that refer mainly to community and households, also the socio-political[20] and market acceptance[21] element have been identified as important. Overall, affordability, engagement of local community, capability of developing regional skill, preservation of biodiversity, safety and distributive benefits to the community, trust in science and technology, familiarity with the technology, existence of energy transition policies in the country of residence have been highlighted as necessary conditions to be fulfilled for increasing acceptance about hydrogen technologies (Emodi et al. 2021); (Vallejos-Romero et al. 2023).

Social impacts are context-driven, and thus **the local dimension** is a key element to consider (Grafakos, Enseñado, and Flamos 2017); (Heras and Martín 2020); (Buchmayr et al. 2022). Some social topics might have both a global and a local dimension, such as human health and safety, labor conditions and job creation, while others are relevant only in the local context, such as those related to the quality of residential life and of landscape (Grafakos, Enseñado, and Flamos 2017); (Buchmayr et al. 2021; 2022). The quality of landscape and of its services refer to the maintenance of aesthetic and visual impacts that might be affected by the installation of technology infrastructures. This social topic has been highlighted as relevant also for hydrogen technologies (Scott and Powells 2020) and is also considered a determinant of public acceptance.

4.3.2.2 Links to social assessment of other renewable energy technologies

Several social topics identified as relevant for hydrogen technologies and systems are also relevant for renewable energy systems in general, with a polarization around the following topics:

- Employment creation and added value creation.
- Supply risks (in terms of labor conditions and human rights).

---

[20] Public trust in government, public trust in the energy sector, public trust in research and development (Gordon, Balta-Ozkan, and Nabavi 2023)

[21] Financial perception, engagement with energy markets, technology perceptions and preferences (Gordon, Balta-Ozkan, and Nabavi 2023).

- Risk for operation (transport, storage).
- Public acceptance.
- Landscape quality.

Nonetheless, social topics such as resilience, energy poverty and energy justice are, relevant for all renewable energy systems, but not anyone system, per se. Rather, these social topics should be addressed at a system level and not at the level of a single technology (see section 4.1 for a definition of the topics). Moreover, there are interdependencies among the social topics, and they are also hierarchically different: energy security can be addressed in terms of supply chain diversification and thus risk reduction in the supply chain, which is also a descriptor of resilience, together with e.g., diversity, adaptive capacity. Accessibility of energy is determined also by affordability, which is also a component of energy justice, together with safety. The definition of a hierarchy of social topics, and their position along the cause-effect chains, is a key requirement for the definition of a conceptual framework of hydrogen technologies and is further addressed in the next chapter.

5 Proposal of a conceptual framework for the social assessment of hydrogen technologies

This chapter describes the conceptual framework for the assessment and monitoring of social risks and impacts related to hydrogen technologies and their value chains. It includes criteria for the definition of the framework's ontology and epistemology, methodological considerations and describes the selected social aspects and indicators.

5.1 Overview of the framework

The conceptual framework lays its foundations in the sustainability science paradigm and life cycle sustainability assessment framework (LCSA defined by Sala et al. (2013a; 2013b)), where ontology is founded on risk and equity, which represent the pillars of social sustainability.

Risks are a threat for people, which have to be protected when vulnerabilities occur (Eizenberg and Jabareen 2017), and the transition to clean energies, including hydrogen, will generate risks but also benefits that impact citizens and society. Ensuring a just and safe transition is then a key priority and represents the overarching goal to be achieved. The framework allows the evaluation of the potential social impacts (or areas of concern and benefits of hydrogen technologies), both at global and local scale. Given that social impacts are context-specific, the knowledge of the local context and the definition of social topics and indicators are necessary, together with those at global level. However, some social impacts that are measured at global scale – such as resilience and justice - might be relevant only when complex technology systems are assessed.

Hydrogen technologies can be evaluated at all levels of technology development, i.e., from when scientific research is at the beginning until the technology is ready to be launched into the market. The limiting factors for any such evaluation are data availability and reliability. This weakness can be partly overcome by adopting a tiered approach. That is, when the level of information is low, either (e.g., due to low TRL or retrievability), a risk-based assessment can be conducted. Using this method, information at country and/or sector level may be retrieved from public sources or social LCA databases such as PSILCA and SHDB, and these databases may provide insights on the likelihood that a certain impact could occur. As a result, vulnerabilities may be identified that provide information useful both for technology developers and policy makers in guiding the upscaling of the technology and understanding the potential social consequences, respectively.

The risk approach is particularly useful for detecting potential social impacts in the supply chain. Since the supply chain often involves extra-EU countries, there may be lower granularity of background data and/or limited sources of information on the social topics related to labour rights and health & safety. The more the information becomes available and the technology is up-scaled, the more information is available so that impacts can be evaluated. At this point, the risk-based approach is likely to be far less used as a basis for the analysis.

Table 8. Characteristics of the conceptual framework for the social assessment of hydrogen technologies. The criteria structure follows those of the LCSA framework by Sala et al. (2013b), further detailed and adapted for the current framework.

CRITERIA OF THE CONCEPTUAL FRAMEWORK	DESCRIPTION
Ontology & epistemology	
Value choices	
Explicit identification of values underpinning the assessment	Risk and equity are the ontological foundations of the framework: 1 Safety and security for humans and non-humans are fundamental requirement of social sustainability and the transition to clean energies has consequences in terms of distribution of risks and benefits on citizens and society (Eizenberg and Jabareen 2017). 2 More justice, less inequality and public involvement enhance capabilities of people to deal with vulnerabilities (Eizenberg and Jabareen 2017).
Completeness of scope	
Encompassing all relevant social aspects of hydrogen technologies	Relevance is defined according to two perspectives (ORIENTING 2023): 3 A social aspect is relevant if it can have an impact, positive or negative, on stakeholders and/or the technology. Hydrogen inherent characteristics with potential implications on social impacts drive the definition of relevance, together with insights from previous studies and literature. 4 A social aspect is relevant because it is considered important by the target audience who desire to have information on them. The social dimension of hydrogen and energy technologies in the policy initiatives, together with the opinions expressed in stakeholders' engagement processes, drive the definition of relevance.
Indirect effects	The underlying life cycle thinking principle accounts for any social aspects along the value chain, i.e., from raw material extraction up to technology installation, use and its dismissal.
Encompassing all the levels of technology development	The framework is capable of addressing social impacts of hydrogen technologies at any technology readiness level.

CRITERIA OF THE CONCEPTUAL FRAMEWORK	**DESCRIPTION**
Encompassing different scales of assessment	The focus of the assessment is at technology level, i.e., single hydrogen technology, but the framework is also able to account for the social consequences generated by the technology at wider scale (meso or macro level). A complete assessment of macro scale effects is however meaningful only in the context of a life cycle sustainability assessment of technology systems.
Geographical and temporal scale	
Global and local aspects	Social impacts might affect the well-being of the population both globally and locally, where the technology is installed. The local dimension is particularly relevant because social impacts are context dependent. Some social impacts address both scales, while others target a specific scale only.
Temporal aspects	The addressed social impacts might refer to present of future situations, depending on the goal and scope of the assessment. Time is a parameter that affects the level of knowledge about the technology under study (e.g., the TRL of the technology), the potential effects of a technology in the future and the effects of the background system in which the technology will be embedded.
Strategic and solution oriented	
Ability to assess alternative scenarios	The definition of scenarios in which the technology will be embedded is possible within the framework. This aspect is linked with the temporal dimension as defined above.
Clear definition of the decision context	The decision context is defined in the goal and scope phase of the social assessment, in which stakeholders affected, scale of the assessment, intended use of the results, relevant social impacts and complexity of the technology are described.
Methodology	
Applicability	
Comparability	The comparison among hydrogen technologies is allowed within the framework, but it is affected by data availability and by a potential asymmetry of information.
Data availability	Data availability changes according to the TRLs and to the type of information to be collected: the lower the TRL, the higher the use of risk-based information based on sector and country specific statistics. At high TRLs, technology-specific information and data can be collected. Data can be qualitative (information), semi-quantitative or quantitative, for the different social aspects.

CRITERIA OF THE CONCEPTUAL FRAMEWORK	DESCRIPTION
	Asymmetry of information might occur when comparing mature technologies vs technologies still under development, or simply technologies with different TRLs. In these situations, the uncertainty of information has to be taken into account and highlighted.
Transparency	Transparency is guaranteed by a thorough documentation of all the choices and underlying assumptions.
Robustness	
Dealing with reliability and uncertainty	There are not yet structured approaches for dealing with uncertainty. Reliability of collected data and information can be investigated through e.g., triangulation, but reliability is affected also by the data granularity. Information/data at country or sector level is reliable if based on recognized sources, and acceptable for a risk-based assessment, but might not describe precisely the technology under study. Market-related information, together with scenario analysis, are useful tool to decrease uncertainty of information and increase the relevance of the results.
Participation of stakeholders	
Stakeholders’ engagement	Stakeholders are the backbone of the social assessment framework, as represent those who suffer the potential social impacts and benefit from positive consequences. They are also a driver of the social assessment, as they determine the success of a technology through their acceptance. Stakeholders are then addressed in the framework under these perspectives: as those against which impacts and benefits are assessed, and those who are engaged in the technology acceptance debate.

Source: authors’ elaboration.

5.2 Methodological considerations

Regarding the **methodology** to be used with the framework, the Social LCA structure and methodology is adopted in relation to the following aspects:

- **Stakeholders**: they are those who experience the social consequences. In the context of the framework for hydrogen technologies the following stakeholders' categories are considered: society, local community, workers, value chain actors. Citizens are represented by both local community and society, depending on the scale of the social effects. Stakeholders have also an active role in determining the acceptance of a technology, as described below.
- **Phases of the methodology** implementation: goal and scope, inventory, risk and performance assessment[22], interpretation.
- **Risk and performance-based assessment**:
    - Risks measure the likelihood that negative effects might occur along the value chain: it is not meant in probabilistic terms, but refer to the plausibility of occurrence, considering statistical data at country and/or sector level.
    - Performances measure the behaviour of the technology in relation to defined social topics. The performance is measured against a known reference, represented by e.g., thresholds, targets as defined in legislation, international conventions, and standards.

Social impacts are also present in the framework, which are better described in terms of **areas of concern**, i.e., a topic defined by the interest of society (Ridoutt et al. 2016). They are not yet quantified through an impact-pathway approach, because the chain of causal links is not developed yet. For this reason, they are measured – like performances and risks - according to the reference scale approach, i.e., data and information on social performances and risks are assessed against a reference scale, which allows comparing an activity/process with a reference point. Reference scales can be defined with a different number of levels: for the application to hydrogen technologies, it is recommended to use the reference scale developed within the ORIENTING project, a four-level scale, and described in ORIENTING (2023).

The **driver-pressure-state-impact-response** (DPSIR approach is used for defining the position of the different social concepts along the cause-effect chain, in line with the SAF (Mancini et al. 2023). Drivers are represented by technical, socio-economic issues that both either characterize the context in which the technology is embedded or are inherent to the technology itself. According to this, they are determinant of social pressures and are identified as part of the context analysis in the goal and scope phase of the framework for hydrogen technologies.

In the context of a social assessment, State refers to a socioeconomic system and thus accounts for features such as living conditions for humans, exposure to the effects of pressures on humans[23]. According to Mancini et al. (2023), in the context of a sustainability assessment State can be represented

---

[22] This terminology is used, instead of impact assessment phase, because in the proposed methodology the focus of the assessment is on risks and performance.

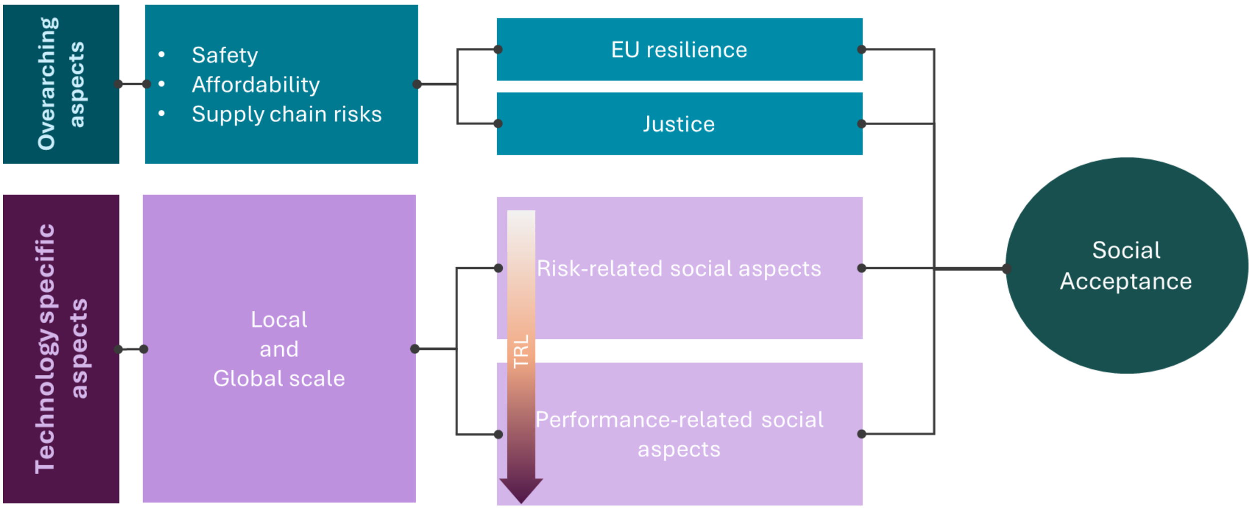
[23] http://www.ejolt.org/2013/02/dpsir/

by technology-specific permitting requirements, because delays on permitting procedures can result in the installation of outdated technologies, with negative effects on competitiveness and energy security.

Impacts are consequences of state change caused by pressures, in terms of socio-economic effects which could be either positive or negative. The classification of the different social topics according to the DPSIR framework is reported in Table 9 and Table 10, together with the list of suggested indicators.

The above-described characteristics of the framework and methodology are represented in Figure 9.

Figure 9. Representation of the framework for assessing and monitoring social risks and impacts related to hydrogen technologies and their value chains.



Source: authors' elaboration.

5.3 Social aspects and indicators

As far as the relevant material social aspects for hydrogen technologies are concerned, their identification is guided by the following twofold approach:

- Relevance is determined by the capability of generating an effect, positive or negative, on stakeholders, due to hydrogen inherent characteristics, as identified in section 4.2. It is also the results of the effects that have been studies and observed in the literature, which are reported in section 4.3.
- Relevance is determined by the interest of the target audience on that specific aspect. The political agenda is then the main reference for identifying the social dimension of hydrogen and energy technologies, together with the opinions of stakeholders who are affected by the technology itself.

Building upon this concept of relevance, and on the ontological foundations of the framework, the following social aspects have been identified as material for hydrogen technologies, which have been structured into two groups, and organized according to the DPSIR framework.

5.3.1 Overarching social aspects of technology systems

This group includes those social aspects that are in the policy agenda of the REPowerEU Plan (EC 2022a and of the European Hydrogen Strategy (EC 2020), aiming at ensuring that the transition towards EU decarbonisation is equitable and beneficial for all. These topics measure effects on society and are applicable mainly at the level of the whole technology/energy system, but some specific social criteria can be measured also for hydrogen technologies. The identified social aspects are reported in Table 9 and refer to *justice* and *resilience*. While security has also been identified as a relevant social aspect, however it is considered to be indirectly captured by justice and resilience through the description of affordability and supply chain risks, respectively.

The social pressures, impacts and indicators reported are those identified as relevant for hydrogen technologies, while other social topics are relevant to consider for these social impact categories if the analysis is carried out at the level of technology systems.

5.3.2 Technology-specific social aspects

These aspects are those relevant and specific for hydrogen technologies. They include both negative and positive effects, target different types of stakeholders and are applicable on a global and/or local scale. The full list is reported in Table 10. The indicators suggested in the table are retrieved from the analyzed literature in section 4, from the methodological sheets on S-LCA (UNEP 2021), from PSILCA database and are adapted and further elaborated as part of this work.

The applicability of the identified social topics depends on the TRL: while at high TRL (demonstration and early adoption and for mature technologies) all the indicators are applicable, because the technology can be already operational. In case of novel technologies, at low TRL (prototype level) details related to the implementation and the final set-up might be missing, and thus the indicators are evaluated in terms of potential risks, i.e., likelihood of their occurrence, informed also by expert judgment and/or country and sector specific information for obtaining an estimate of the social aspect under analysis.

Depending on the outcomes of the evaluation of the identified social aspects, it is possible to conclude on a potential acceptance of the technology, which represents the Response according to the DPSIR framework. Thus, acceptance represents the results of the assessment process. Indeed, acceptance is driven also by perceptions of risks and benefits, in addition to cultural aspects, and represents thus the response of stakeholders to the pressures along the value chain.

Table 9. Overarching social aspects and related indicators of hydrogen technologies.

Areas of concern/Impact		**Social topic/Pressure**		**Indicator**
Justice **(a global energy system that fairly disseminates both the benefits and costs of energy/technology services, and one that has representative and impartial energy decision-making (Sovacool 2017).**				
	Safety	Risks for the population	Risk estimates for normal operations	— Mortality due to normal operations (YOLL/kg hydrogen) — Morbidity due to normal operation (DAILY/kg hydrogen)
			Risks estimates for accidents	— Expected mortality due to sever accidents (fatalities/kg hydrogen) — Maximum credible number of fatalities per accident (fatalities/accident)
	Affordability			Different indicators can be used, depending on the application. Main approaches identified in literature (Lin 2018), adapted from the energy context: — fixed threshold of service provided by the technology expenditure versus income. — relative measure where the threshold is set relative to the average expenditure on the service. — a residual income approach measures affordability based on the idea that a household must make certain purchases beyond utilities.
Resilience **(Ability to reduce and withstand the magnitude and/or duration of disruptive effects, which include the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.[24]).**				
		Diversity in market, suppliers and technologies		Supply chain concentration: — geographic concentration: the extent to which production is concentrated in a single geographic area (ordinal scale) — market concentration: the extent to which production is concentrated — in a single company (ordinal scale) — technology concentration: the extent to which global production is centered on a single technology (ordinal scale)
	Supply chain risk	Risk of disruption		— Supply risk as defined in the EC methodology 2017 — Share of materials with high geopolitical risk of disruption (Geopolrisk indicators, both midpoint (Gemechu et al. 2016); Helbig et al. 2016 and endpoint. The latter (GeoPolEndpoint translates – through monetization - the potential increase of costs of production due to supply disruption into a socio-economic damage (Santillán-Saldivar et al., 2022).

---

[24] https://www.law.cornell.edu/uscode/text/42/17384a#j. Accessed July 2024

		Risk of contributing to human right infractions and conflicts[25] and corruption		— Human rights indicators as defined by United Nations Human Rights and available in the OHCHR26 database — Level of corruption, based on Corruption Perceptions Index[27] (ordinal scale)
		Risk of contributing to adverse labor conditions	Freedom of association and collective bargaining	— Trade union density (% of employees organized in trade unions) — Right of association (ordinal scale) — Right of collective bargaining (ordinal scale) — Right to strike (ordinal scale)
			Fair salary	— Living wage, per month — Minimum wage, per month — Sector average wage, per month
			Forced labor	— Risk of forced labor in the country (cases per 1,000 inhabitants) — Risk of forced labor in the sector (ordinal scale)

Source: authors' elaboration.

Table 10. Specific social aspects and indicators of hydrogen technologies

Areas of concern/impact	**Social topic/pressure**		**Scale**	**Stakeholder**	**indicator**
Working conditions (excluding the supply chain)	Health and safety risks		Global and local	Worker	— Rate of non-fatal accidents at workplace (cases per 100.000 employees and year) — Rate of fatal accidents at workplace (cases per 100.000 employees and year) — Presence of sufficient safety measures (OSHA cases per 100.000 employees in the sector)
	Forced labor				— Risk of forced labor in the country (cases per 1,000 inhabitants) — Risk of forced labor in the sector (ordinal scale)
	Freedom of association and collective bargaining				— Trade union density (% of employees organized in trade unions) — Right of association (ordinal scale) — Right of collective bargaining (ordinal scale) — Right to strike (ordinal scale)
	Child labor				— % of all children ages 7-14
	Fair salary				— Living wage, per month — Minimum wage, per month

---

[25] Some of the issues accounted for in human rights respect might be also accounted for in the topic related to labor conditions (e.g., child labor, gender inequalities). Care is necessary to avoid double counting.

[26] Office of High Commissioner for Human Rights https://www.ohchr.org/en/instruments-and-mechanisms/human-rights-indicators/sdg-indicators-under-ohchrs-custodianship.

[27] The Corruption Perception Index ranks 180 countries and territories around the world by their perceived levels of public sector corruption, scoring on a scale of 0 (highly corrupt to 100 (very clean). https://www.transparency.org/en/cpi/2022?gclid=CjwKCAiAnL-sBhBnEiwAJRGigtfUIx7U-3FS9NCxG1BDjkFEexSuSkBsWKNEY6oBwfseq9bF-7PiIhoCwbQQAvD_BwE&gad_source=1

					— Sector average wage, per month
	Working hour				— Hours of work per employee, per week
Technology innovation potential			Global	Society	Patents (Wulf an Zapp 2021): — Technology potential: Patent growth rate in % of this technology for a defined time period (Growth potential of the technology) — National technology share: Number of patents in this field in relation to all national patents (Relevance of a certain technology for a country) — Patent activity: Sum of patents of a technology in a country (Extent of R&D expenditures)
Socio-economic repercussions	Employment and added value	Job creation	Global and local	Local community & Society	— Knowledge intensive jobs (% high-skilled employees[28]/total employees required for kg hydrogen) — Total employment (person-years/r kg hydrogen) — Local employment (proportion of employees hired from local community/total employment)
		Job creation including quality (working conditions quality)			— Based on OECD framework. Details available in Buchmayr et al. (2022 and in section 4.3.2
	Access to material resources			Local community	— The extent to which the technology creates adverse impacts on access to material and immaterial resources, and cultural heritage for local communities (ordinal scale)
	Contribution to economic development				— Contribution of the technology to economic development (% of GDP)
	Flexibility[29]				— Flexibility to adapt to different contexts (ordinal scale, expert judgment)
Quality of life	Quality of landscape		Local	Local community	— Aesthetic impacts (Likert scale, expert judgment) — Noise exposure (Likert scale, expert judgment) — Contribution to traffic (total traffic load, km/kg hydrogen)
	Governance of the value chain	Wealth[30] distribution		Value chain actors	Different economic indicators are used in the literature. Some examples: net operating profits, return on turnover, benchmarks for suppliers' net income. This is an aspect for future development of the framework.

Source: authors' elaboration.

---

[28] High-skilled employees include managers, professionals, technicians and associate professionals for which education is required (van Haaster et al. 2017)

[29] Renewable hydrogen can also support the EU's electricity sector, providing long-term and large-scale storage. Thanks to its storage potential, hydrogen is considered to improve the flexibility of energy systems by balancing out supply and demand when there is either too much or not enough power being generated. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

[30] It evaluates the extent to which the value is distributed in an equitable way to all the actors of the value chain (UNEP 2021).

6 Conclusions

The proposed framework aims at guiding the assessment of social impacts of hydrogen technologies, and it is conceived to be used both as stand-alone framework but also to be compatible with the LCSA (Sala, Farioli, and Zamagni 2013a; 2013b) and more specifically the SAF (Mancini et al. 2023) developed by JRC. The proposal is an attempt to go beyond limitations of existing approaches for social assessment in relation to three main aspects:

- Defining the theoretical background of the social assessment in terms of ontology and epistemology, as a basis for informing the definition of the methodology and the identification of the social indicators. Currently, most of the available approaches in S-LCA are concentrated on identifying suitable indicators, but without justifying or explicating the underlying theoretical concept.

- Making the assessment suitable for technologies, at different TRL: this required overcoming the organisational perspective typical of the S-LCA methodology and defining technology-specific requirements, i.e., social topics that characterise the technology under study, independently by who manages them. The implication is that the object of the analysis is different compared to current S-LCA studies, and that the analysis is carried out under conditions of uncertainty because the context of operation of the technology might not be known.

Being a conceptual framework, its full implementation will require additional developments, especially in relation to the detailed definition of the methodology, a guidance for its application and the quantification and measurement of the proposed social indicators. Currently, not for all the social aspects suitable indicators have been identified, in particular for measuring affordability and quality of landscape, and also wealth distributions along the value chain, i.e., inequalities among actors, is an area of development considered of interest, given the international dimension of the hydrogen value chain. Approaches are present in literature (Lang, Ponte and Vilakazi 2022) but further investigation is needed. In addition, the elaboration of these indicators according to the reference scale requires additional development, as well as their aggregation within the performance indicators and among performance and risk indicators. While it is always advisable to keep the results as much disaggregated as possible, however a condense overview of the results would ease the understanding of the results.

As a support to the framework development, a case study will be carried out, aiming at testing its applicability and the data and information availability for measuring the proposed indicators, considering technologies at different TRLs.

References

Abu-Rayash, Azzam, and Ibrahim Dincer. 2019. "Sustainability assessment of energy systems: A novel integrated model." Journal of Cleaner Production 212 (2019): 1098-1116.

Acar, Canan, Ahmet Beskese, and Gul Tekin Temur. 2022. “Comparative Fuel Cell Sustainability Assessment with a Novel Approach.” International Journal of Hydrogen Energy 47 (1): 575–94. https://doi.org/10.1016/j.ijhydene.2021.10.034.

Afgan, Naim H., and Maria G. Carvalho. 2004. “Sustainability Assessment of Hydrogen Energy Systems.” International Journal of Hydrogen Energy 29 (13): 1327–42. https://doi.org/10.1016/j.ijhydene.2004.01.005.

Akhtar, Malik Sajawal, Hafsa Khan, J. Jay Liu, and Jonggeol Na. 2023. “Green Hydrogen and Sustainable Development – A Social LCA Perspective Highlighting Social Hotspots and Geopolitical Implications of the Future Hydrogen Economy.” Journal of Cleaner Production 395 (April). https://doi.org/10.1016/j.jclepro.2023.136438.

Almaraz, S. D. L., Kocsis, T., Azzaro-Pantel, C., & Szántó, Z. O. (2023). Identifying social aspects related to the hydrogen economy: Review, synthesis, and research perspectives. International Journal of Hydrogen Energy.

Arrigoni, A., Dolci, F., Ortiz Cebolla, R., Weidner, E., D’agostini, T., Eynard, U., Santucci, V. and Mathieux, F., Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe, Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/5459, JRC137953.

Arrigoni, A. and Bravo Diaz, L., Hydrogen emissions from a hydrogen economy and their potential global warming impact, EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4, doi:10.2760/065589, JRC130362.

Azadnia, Amir Hossein, Conor McDaid, Amin Mahmoudzadeh Andwari, and Seyed Ehsan Hosseini. 2023. “Green Hydrogen Supply Chain Risk Analysis: A European Hard-to-Abate Sectors Perspective.” Renewable and Sustainable Energy Reviews 182 (August). https://doi.org/10.1016/j.rser.2023.113371.

Bargiacchi, Eleonora, Felipe Campos-Carriedo, Diego Iribarren, and Javier Dufour. 2022. “Social Life Cycle Assessment of a Proton Exchange Membrane Fuel Cell Stack.” In E3S Web of Conferences. Vol. 334. EDP Sciences. https://doi.org/10.1051/e3sconf/202233409001.

Ben Hnich, Khaoula; Maddula, Sumanth K.R; Merlo, Laura; Iribarren, Diego; Carbone, Claudio; Nawaya, Tarik; Bereketidou, Olga; Brière, Raphaël; Maranghi, Simone; Bachmann, Till M; Beretta, Davide. 2024. Deliverable 2.2 FCH Product Categories. HyPEF Project, GA 101137575

Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Talens Peirò, L., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements, Resources Policy, Volume 53, 2017, Pages 12-19, ISSN 0301-4207, https://doi.org/10.1016/j.resourpol.2017.05.008.

Blohm, Marina, and Franziska Dettner. 2023. “Green Hydrogen Production: Integrating Environmental and Social Criteria to Ensure Sustainability.” Smart Energy 11 (August). https://doi.org/10.1016/j.segy.2023.100112.

Bolard, J., Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E. and Shtjefni, D., Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/133010, JRC135018.

Buchmayr, A., E. Verhofstadt, L. Van Ootegem, D. Sanjuan Delmás, G. Thomassen, and J. Dewulf. 2021. “The Path to Sustainable Energy Supply Systems: Proposal of an Integrative Sustainability Assessment Framework.” Renewable and Sustainable Energy Reviews. Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.110666.

Buchmayr, A., E. Verhofstadt, L. Van Ootegem, G. Thomassen, S. E. Taelman, and J. Dewulf. 2022. “Exploring the Global and Local Social Sustainability of Wind Energy Technologies: An Application of a Social Impact Assessment Framework.” Applied Energy 312 (April). https://doi.org/10.1016/j.apenergy.2022.118808.

Buffi, M., Scarlat N., Hurtig O., Motola V., Georgakaki A., Letout S., Mountraki A., Joanny G., Clean Energy Technology Observatory: Renewable Fuels of Non-Biological Origin in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/76717, JRC130729.

Calabrese M, Portarapillo M, Di Nardo A, Venezia V, Turco M, Luciani G, Di Benedetto A. Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies*. 2024; 17(6):1350. https://doi.org/10.3390/en17061350

Caldeira, C., Farcal, L., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials. KJ-NA-31100-EN-N (online),KJ-NA-31100-EN-C (print). https://doi.org/10.2760/487955 (online),10.2760/404991 (print)

Campos-Carriedo, Felipe, Dufour, Javier, and Diego Iribarren. 2024. “Towards suitable practices for the integration of social life cycle assessment into the ecodesign framework of hydrogen-related products.” Sustainable Production and Consumption Volume 46, 2024, Pages 29-39,

Carbajo, Ruth, and Luisa F. Cabeza. 2019. “Sustainability and Social Justice Dimension Indicators for Applied Renewable Energy Research: A Responsible Approach Proposal.” Applied Energy. Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2019.113429.

Carr-Cornish, Simone, Krystina Lamb, Michelle Rodriguez, and John Gardner. 2019. “Social Science for a Hydrogen Energy Future A Review of Existing Knowledge, Potential Risks from Society’s Response, and Science Pathways for Social Responsibility.”

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D., Christou, M., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889

Carrera, Diana Gallego, and Alexander Mack.2010. "Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts." Energy policy 38.2 (2010): 1030-1039.

Ciroth, Andreas, Di Noi, Claudia, and Michael Srocka. 2019. Revisiting the activity variable in social LCA – Beyond worker hours. In: LCA XIX. Tucson. [Online]. Available: https://www. greendelta.com/wp-content/uploads/2019/11/2019_LCA_XIX_Revisiting-the-activit y-variable-in-SLCA.pdf.

Clean Hydrogen Partnership 2023. Programme Review. Report 2023. ISBN 978-92-9246-414-1

Costa, Ericka, and Caterina Pesci. 2016. "Social impact measurement: why do stakeholders matter?." Sustainability Accounting, Management and Policy Journal 7.1 (2016): 99-124.

Dillman, K. J., and J. Heinonen. 2022. "A 'Just' Hydrogen Economy: A Normative Energy Justice Assessment of the Hydrogen Economy." Renewable and Sustainable Energy Reviews 167 (October). https://doi.org/10.1016/j.rser.2022.112648.

Dincer, Ibrahim. 2007. "Environmental and Sustainability Aspects of Hydrogen and Fuel Cell Systems." International Journal of Energy Research 31 (1): 29–55. https://doi.org/10.1002/er.1226.

EC. 2017. European Commission, Secretariat-General, European pillar of social rights, Publications Office, https://data.europa.eu/doi/10.2792/95934

EC. 2018. European Commission, Directorate-General for Research and Innovation, Joint Research Centre, The strategic energy technology (SET plan, Publications Office, 2018, https://data.europa.eu/doi/10.2777/04888

EC. 2019. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM (2019 640 final.

EC. 2020. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions. A hydrogen strategy for a climate-neutral Europe. COM (2020 301 final

EC. 2021. Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the regions. 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. COM/2021/550 final

EC. 2022a. Communication from the Commission to the European Parliament, the European Council, the Council, the European economic and social committee and the Committee of the regioins. REPowerEU Plan. COM/2022/230 final

EC. 2022b. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Corporate Sustainability Due Diligence and amending Directive (EU 2019/1937 COM/2022/71 final

EC. 2022c. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on prohibiting products made with forced labour on the Union market. COM(2022 453 final

EC. 2024. Regulation (EU 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials

Eizenberg, Efrat, and Yosef Jabareen. 2017. "Social Sustainability: A New Conceptual Framework." Sustainability (Switzerland 9 (1). https://doi.org/10.3390/su9010068.

Emodi, Nnaemeka Vincent, Heather Lovell, Clinton Levitt, and Evan Franklin. 2021. "A Systematic Literature Review of Societal Acceptance and Stakeholders' Perception of Hydrogen Technologies."

International Journal of Hydrogen Energy. Elsevier Ltd. https://doi.org/10.1016/j.ijhydene.2021.06.212.

Fortier, Marie Odile P., Lemir Teron, Tony G. Reames, Dynta Trishana Munardy, and Breck M. Sullivan. 2019. “Introduction to Evaluating Energy Justice across the Life Cycle: A Social Life Cycle Assessment Approach.” Applied Energy 236 (February): 211–19. https://doi.org/10.1016/j.apenergy.2018.11.022.

Gemechu, E. D., Helbig, C., Sonnemann, G., Thorenz, A., & Tuma, A. (2016). Import-based indicator for the geopolitical supply risk of raw materials in life cycle sustainability assessments. Journal of Industrial Ecology, 20(1), 154-165

Germscheidt, Rafael L., Moreira, Daniel E., Yoshimura, Rafael G., Gasbarro, Nathalia P., Datti, Evandro, dos Santos, Pãmyla L., & Bonacin, Juliano A. 2021. “Hydrogen environmental benefits depend on the way of production: An overview of the main processes production and challenges by 2050”. Advanced Energy and Sustainability Research, 2(10), 2100093. https://doi.org/10.1002/aesr.202100093

Gnanapragasam, Nirmal V., Bale V. Reddy, and Marc A. Rosen. 2010. “A Methodology for Assessing the Sustainability of Hydrogen Production from Solid Fuels.” Sustainability 2 (6): 1472–91. https://doi.org/10.3390/su2061472.

Goedkoop, Mark, Ilonka de Beer, Rosan Harmens, Peter Saling, Dave Morris, Alexandra Florea, Anne Laure Hettinger, et al. 2020. “Product Social Impact Assessment Handbook.”

Gordon, Joel A., Nazmiye Balta-Ozkan, and Seyed Ali Nabavi. 2023. “Price Promises, Trust Deficits and Energy Justice: Public Perceptions of Hydrogen Homes.” Renewable and Sustainable Energy Reviews 188 (December): 113810. https://doi.org/10.1016/j.rser.2023.113810.

Grafakos, Stelios, Elena Marie Enseñado, and Alexandros Flamos. 2017. “Developing an Integrated Sustainability and Resilience Framework of Indicators for the Assessment of Low-Carbon Energy Technologies at the Local Level.” International Journal of Sustainable Energy 36 (10): 945–71. https://doi.org/10.1080/14786451.2015.1130709.

Haase, M., C. Wulf, M. Baumann, C. Rösch, M. Weil, P. Zapp, and T. Naegler. 2022. “Prospective Assessment of Energy Technologies: A Comprehensive Approach for Sustainability Assessment.” Energy, Sustainability and Society 12 (1). https://doi.org/10.1186/s13705-022-00344-6.

Haaster, Berthe van, Andreas Ciroth, João Fontes, Richard Wood, and Andrea Ramirez. 2017. “Development of a Methodological Framework for Social Life-Cycle Assessment of Novel Technologies.” International Journal of Life Cycle Assessment 22 (3): 423–40. https://doi.org/10.1007/s11367-016-1162-1.

Hake, Jürgen Friedrich, Jan Christian Koj, Wilhelm Kuckshinrichs, Holger Schlör, Andrea Schreiber, Christina Wulf, Petra Zapp, and Thomas Ketelaer. 2017. “Towards a Life Cycle Sustainability Assessment of Alkaline Water Electrolysis.” In Energy Procedia, 105:3403–10. Elsevier Ltd. https://doi.org/10.1016/j.egypro.2017.03.779.

Hallste Pérez, Teresa, Jorge Rodríguez-Chueca, and Javier Pérez Rodríguez. 2023. “Inclusion of Key Social Indices for a Comparative Assessment of the Sustainability of the Life Cycle of Current and Future Electricity Generation in Spain: A Proposed Methodology.” Science of the Total Environment 899 (November). https://doi.org/10.1016/j.scitotenv.2023.165541.

Hanusch, Frederic, and Miriam Schad. 2021. “Hydrogen Research: Technology First, Society Second?” GAIA - Ecological Perspectives for Science and Society. Oekom Verlag. https://doi.org/10.14512/GAIA.30.2.5.

Helbig, C., Gemechu, E. D., Pillain, B., Young, S. B., Thorenz, A., Tuma, A., & Sonnemann, G. (2016). Extending the geopolitical supply risk indicator: Application of life cycle sustainability assessment to the petrochemical supply chain of polyacrylonitrile-based carbon fibers. Journal of Cleaner Production, 137, 1170-1178.

Heras, Jorge, and Mariano Martín. 2020. “Social Issues in the Energy Transition: Effect on the Design of the New Power System.” Applied Energy 278 (November). https://doi.org/10.1016/j.apenergy.2020.115654.

Hirschberg, Stefan, et al.2008. "Deliverable n D3. 2–RS 2b “Final set of sustainability criteria and indicators for assessment of electricity supply options”." NEEDS-New Energy Externalities Developments for Sustainability; Project 502687 (2008).

Hydrogen Europe (2023 Hydrogen Europe Position Paper June 2023 2023 Critical Raw Materials Act – Hydrogen Europe’s views. June 2023

International Energy Agency (2024) Global Hydrogen Review. October 2024.

International Energy Agency (2020) Energy Policy Review. June 2020

International Energy Agency (2022) Securing Clean Energy Technology Supply Chains.

Iribarren, Diego, and Javier Dufour. 2018. IEA Hydrogen Task 36-Life Cycle Sustainability Assessment of Hydrogen Energy Systems-Final Report.

Lang, J., Ponte, S., & Vilakazi, T. (2023). Linking power and inequality in global value chains. Global Networks, 23(4), 755-771.

László Pintér, Peter Hardi, André Martinuzzi, and Jon Hall. 2018. Bellagio STAMP Principles for Sustainability Assessment and Measurement.

Lin J (2018 Affordability and access in focus: Metrics and tools of relative energy vulnerability. The Electricity Journal, Volume 31, Issue 6, July 2018, Pages 23-32

Mancini, L., Eynard, U., Eisfeldt, F., Ciroth, A., Blengini, G. A., & Pennington, D. W. 2018. Social Assessment Of Raw Materials Supply Chains: A Life-Cycle-Based Analysis. Publications Office of the European Union. https://doi.org/10.2760/470881

Mancini Lucia, Leccisi Enrica, Carla Patinha Caldeira, and Sala Serenella. 2023. “Proposal for a Sustainability Framework for Energy Technologies.” Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/11063, JRC135255.

Martín-Gamboa, Mario, Ana Cláudia Dias, Luis Arroja, and Diego Iribarren. 2020. “A Protocol for the Definition of Supply Chains in Product Social Life Cycle Assessment: Application to Bioelectricity.” Sustainable Energy and Fuels 4 (11): 5533–42. https://doi.org/10.1039/d0se00919a.

Martín-Gamboa, Mario, Ana Cláudia Dias, and Diego Iribarren. 2022. “Definition, Assessment and Prioritisation of Strategies to Mitigate Social Life-Cycle Impacts across the Supply Chain of Bioelectricity: A Case Study in Portugal.” Renewable Energy 194 (July): 1110–18. https://doi.org/10.1016/j.renene.2022.06.002.

Martín-Gamboa, Mario, Mancini, Lucia, Eynard, Umberto, Arrigoni, Alessandro, Valente, Antonio, Weidner, Eveline, and Mathieux, Fabrice. 2024. “Social life cycle hotspot analysis of future hydrogen use in the EU”. The International Journal of Life Cycle Assessment, 1-18. https://doi.org/10.1007/s11367-024-02335-5

Moradi, Ramin, and Katrina M. Groth. 2019. “Hydrogen Storage and Delivery: Review of the State of the Art Technologies and Risk and Reliability Analysis.” International Journal of Hydrogen Energy. Elsevier Ltd. https://doi.org/10.1016/j.ijhydene.2019.03.041.

Mori, Mitja, Diego Iribarren, Julie Cren, Emmanuelle Cor, Andrej Lotrič, Jure Gramc, Boštjan Drobnič, et al. 2023. “Life Cycle Sustainability Assessment of a Proton Exchange Membrane Fuel Cell Technology for Ecodesign Purposes.” International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2023.05.255.

Muller, Stéphanie, Antoine Beylot, Olga Sydd, Keiran Doyle, Jérôme Bodin, and Jacques Villeneuve. 2021. “Applying Social Life Cycle Assessment in the Early Stages of a Project Development — an Example from the Mining Sector.” International Journal of Life Cycle Assessment 26 (12): 2436–56. https://doi.org/10.1007/s11367-021-01995-x.

Noi, Claudia Di, Andreas Ciroth, Lucia Mancini, Umberto Eynard, David Pennington, and Gian Andrea Blengini. 2020. “Can S-LCA Methodology Support Responsible Sourcing of Raw Materials in EU Policy Context?” International Journal of Life Cycle Assessment 25 (2): 332–49. https://doi.org/10.1007/s11367-019-01678-8.

ORIENTING. 2023. (D2.5 Specification of social indicators for LCSA. Authors: L. Zanchi, A. Zamagni, S. Pillay, D. Mangana, H. Pihkola, E. Paronen, E. Hylkilä, T. Sonderegger, E. C. Martinez, P. Saling, M. Isasa, R. Ugarte. EU Horizon 2020 project ORIENTING (GA No 958231).

Ortiz Cebolla, R., Dolci, F. and Weidner Ronnefeld, E., Assessment of hydrogen delivery options, EUR 31199 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-56421-8, doi:10.2760/869085, JRC130442.

Piasna, Agnieszka.2023. "Job quality in turbulent times: An update of the European Job Quality Index." ETUI Research Paper-Working Paper.

ORIENTING. 2024. (D2.9 LCSA Handbook. Authors: Hanna Pihkola, Marina Isasa, Till M. Bachmann, Jonathan van der Kamp, Laura Zanchi, Alessandra Zamagni, Katri Behm, Rafael Horn, Isadora Correa, Lilian Sanchez Moreno. EU Horizon 2020 project ORIENTING (GA No 958231).

Ravitch SM, Riggan M (2016 Reason and rigor: how conceptual frameworks guide research (2nd ed. Thousand Oaks, CA:Sage

Ridoutt, B. G., Pfister, S., Manzardo, A., Bare, J., Boulay, A. M., Cherubini, F., ... & Verones, F. (2016). Area of concern: a new paradigm in life cycle assessment for the development of footprint metrics. The International Journal of Life Cycle Assessment, 21, 276-280.

Rugolo, J., & Aziz, M. J. (2012). Life-cycle hydrogen emissions and the consequences for future hydrogen economies. Energy Policy, 46, 645-655.

RMIS (2025) Raw Materials Information System – Raw Materials Profiles available at: https://rmis.jrc.ec.europa.eu/rmp/

Sala, Serenella, Francesca Farioli, and Alessandra Zamagni. 2013a. “Progress in Sustainability Science: Lessons Learnt from Current Methodologies for Sustainability Assessment: Part 1.”

International Journal of Life Cycle Assessment 18 (9): 1653–72. https://doi.org/10.1007/s11367-012-0508-6.

Sala, Serenella, Francesca Farioli, and Alessandra Zamagni. 2013b. “Life Cycle Sustainability Assessment in the Context of Sustainability Science Progress (Part 2).” International Journal of Life Cycle Assessment 18 (9): 1686–97. https://doi.org/10.1007/s11367-012-0509-5.

Sala, S., Amadei, A. M., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. The International Journal of Life Cycle Assessment, 26, 2295-2314.

Santillán-Saldivar, J., Gemechu, E., Muller, S., Villeneuve, J., Young, S. B. (2022). An improved resource midpoint characterization method for supply risk of resources : integrated assessment of Li - ion batteries. The International Journal of Life Cycle Assessment, 0123456789. https://doi.org/10.1007/s11367-022-02027-y

Santoyo-Castelazo, Edgar, and Adisa Azapagic. 2014. “Sustainability Assessment of Energy Systems: Integrating Environmental, Economic and Social Aspects.” Journal of Cleaner Production 80 (October): 119–38. https://doi.org/10.1016/j.jclepro.2014.05.061.

Schlör, Holger, and Sandra Venghaus.2022. "A stakeholder impact analysis of the production of the energy vector hydrogen." Environmental Assessment of Renewable Energy Conversion Technologies. Elsevier, 2022. 231-247.

Schönauer, Anna Lena, and Sabrina Glanz. 2022. “Hydrogen in Future Energy Systems: Social Acceptance of the Technology and Its Large-Scale Infrastructure.” International Journal of Hydrogen Energy 47 (24): 12251–63. https://doi.org/10.1016/j.ijhydene.2021.05.160.

Scott M, and Powells G. 2020. “Towards a New Social Science Research Agenda for Hydrogen Transitions: Social Practices, Energy Justice, and Place Attachment.”

Social & Human Capital Coalition. (2018, April). Draft: The Social & Human Capital Protocol. Retrieved from https://docs.wbcsd.org/2019/02/Social_and_Human_Capital_Protocol.pdf

Ravitch, Sharon M., and Matthew Riggan. Reason & rigor: How conceptual frameworks guide research. Sage Publications, 2016.

Soltanpour, Yazdan, Iuri Peri, and Leïla Temri. 2019. “Area of Protection in S-LCA: Human Well-Being or Societal Quality.” International Journal of Life Cycle Assessment 24 (11): 2073–87. https://doi.org/10.1007/s11367-019-01620-y.

Sovacool, B. K., Burke, M., Baker, L., Kotikalapudi, C. K., & Wlokas, H. (2017). New frontiers and conceptual frameworks for energy justice. Energy Policy, 105, 677–691. https://doi.org/https://doi.org/10.1016/j.enpol.2017.03.005

Stamford, Laurence, and Adisa Azapagic. 2012. “Life Cycle Sustainability Assessment of Electricity Options for the UK.” International Journal of Energy Research 36 (14): 1263–90. https://doi.org/10.1002/er.2962.

Wells,Thomas R. 2012. “Sen’s Capability Approach.” In Internet Encyclopedia of Philosophy , edited by J. Feiser & B. Dowden.

Trinomics and Artelys. 2021. Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis. Final Report. ISBN 978-92-76-38453-3, doi:10.2833/946002

UNEP. 2012. Application of the Sustainability Assessment of Technologies methodology: Guidance manual.

UNEP. 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. Edited by C Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, et al.

UNEP. 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA (M. Traverso, S. Valdivia, A. Luthin, L. Roche, G. Arcese, S. Neugebauer, L. Petti, M. D'Eusanio, B. M. Tragnone, R. Mankaa, J. Hanafi, C. Benoit-Norris, & A. Zamagni (eds.)).

UN General Assembly. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. In New York: United Nations.

Valdivia, Sonia, Jana Gerta Backes, Marzia Traverso, Guido Sonnemann, Stefano Cucurachi, Jeroen B. Guinée, Thomas Schaubroeck, et al. 2021. "Principles for the Application of Life Cycle Sustainability Assessment." International Journal of Life Cycle Assessment 26 (9): 1900–1905. https://doi.org/10.1007/s11367-021-01958-2.

Valente, Antonio, D. Iribarren, and Javier Dufour. 2019. "Life Cycle Sustainability Assessment of Hydrogen from Biomass Gasification: A Comparison with Conventional Hydrogen." International Journal of Hydrogen Energy 44 (38): 21193–203. https://doi.org/10.1016/j.ijhydene.2019.01.105.

Valente, Antonio, Diego Iribarren, and Javier Dufour. 2021. "Comparative Life Cycle Sustainability Assessment of Renewable and Conventional Hydrogen." Science of the Total Environment 756 (February). https://doi.org/10.1016/j.scitotenv.2020.144132.

Vallejos-Romero, Arturo, Minerva Cordoves-Sánchez, César Cisternas, Felipe Sáez-Ardura, Ignacio Rodríguez, Antonio Aledo, Álex Boso, Jordi Prades, and Boris Álvarez. 2023. "Green Hydrogen and Social Sciences: Issues, Problems, and Future Challenges." Sustainability (Switzerland). MDPI. https://doi.org/10.3390/su15010303.

Vezzoli C, Ceschin F, Osanjo L, M'Rithaa MK, Moalosi R, Nakazibwe V, Diehl JC (2018 Designing Sustainable Energy for All Sustainable Product-Service System Design Applied to Distributed Renewable Energy. Springer ISBN 978-3-319-70222-3, https://doi.org/10.1007/978-3-319-70223-0

Werker, Jasmin, Christina Wulf, and Petra Zapp. 2019. "Working Conditions in Hydrogen Production: A Social Life Cycle Assessment." Journal of Industrial Ecology 23 (5): 1052–61. https://doi.org/10.1111/jiec.12840.

Wulf, Christina, and Petra Zapp. 2021. "Sustainability Assessment of Innovative Energy Technologies – Hydrogen from Wind Power as a Fuel for Mobility Applications." Journal of Sustainable Development of Energy, Water and Environment Systems 9 (3). https://doi.org/10.13044/j.sdewes.d8.0371.

Zamagni, Alessandra, Oscar Amerighi, and Patrizia Buttol. 2011. "Strengths or Bias in Social LCA?" International Journal of Life Cycle Assessment 16 (7). https://doi.org/10.1007/s11367-011-0309-3.

List of abbreviations and definitions

Abbreviations	Definitions
CRMA	Critical Raw Materials Act
DALY	Disability Adjusted Life Years
DIS	Draft International Standard
DPSIR	Driver-Pressure-State-Impact-Response
EC	European Commission
EU	European Union
FCH-JU	Fuel Cells and Hydrogen Joint Undertaking
GWP	Global Warming Potential
IEA	International Energy Agency
JRC	Joint Research Centre
LCSA	Life Cycle Sustainability Assessment
LCA	Life Cycle Assessment
OHCHR	Office of the United Nations High Commissioner for Human Rights
PSILCA	Product Social Impact Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
SAT	Sustainability Assessment of Technology
SHDB	Social Hotspot Database
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme
YOLL	Years of Lost Life

List of figures

List of tables

Annex 1

Table 11. ORIENTING list of social topics and concerned stakeholder groups

No	Social topics	Stakeholder groups						
		Worker	Local community	User/consumer	Small scale enterpreneurs	Value chain actors	Society	Children
1	Access to material, immaterial resources and cultural heritage		X					
2	Accessibility			X				
3	Affordability			X				
4	Child labour	X			X			X
5	Community engagement		X					
6	Contribution to economic development (including local employment)		X					
7	Corruption						X	
8	Delocalization and migration		X					
9	Discrimination and equal opportunities	X			X			
10	Effectiveness and comfort			X				
11	End of life responsibility			X	X	X		
12	Ethical treatment of animals						X	
13	Fair competition				X	X		
14	Forced labour	X						
15	Freedom of association and collective bargaining	X						
16	Health and safety (worker)	X			X	X		X
17	Health and safety (user))			X				
18	Safe, healthy and secure living conditions		X					

No	**Social topics**	**Stakeholder groups**						
		Worker	**Local community**	**User/consumer**	**Small scale enterpreneurs**	**Value chain actors**	**Society**	**Children**
19	Prevention and mitigation of armed conflicts						X	
20	Privacy			X				
21	Promoting social responsibility and public commitment to sustainability issues					X		
22	Remuneration and social benefits	X			X			
23	Respect of indigenous rights and land rights		X		X			
24	Respect of intellectual property rights					X		
25	Responsible communication and feedback mechanisms			X				
26	Skill and technology development		X				X	
27	Supplier relationships and fair trading				X	X		
28	Women’s empowerment				X			
29	Work life balance and working hours	X			X			

Source: ORIENTING 2023

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Publications Office
of the European Union