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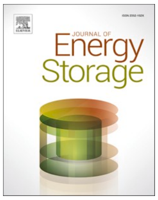

Research papers

Life Cycle Assessments in hydrogen-based energy storage systems

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ABSTRACT

Hydrogen is increasingly recognized as an element in the effort to decarbonize the energy sector. Within the development of large-scale supply chain, the storage phase emerges as a significant challenge. This study reviews Life Cycle Assessment (LCA) literature focused exclusively on hydrogen as an energy vector, aiming to identify areas for improvement, highlight effective solutions, and point out research gaps. The goal is to provide a comprehensive overview of hydrogen storage technologies from an environmental perspective. A systematic search was conducted in the SCOPUS database using a specific set of keywords, resulting in the identification of 30 relevant studies. These works explore hydrogen storage across different scales and applications, which were classified into five categories based on the type of storage application, most of them related to stationary use. The majority of the selected studies focus on storing hydrogen in compressed gas tanks. Notably, 33 % of the analyzed articles assess only greenhouse gas (GHG) emissions, and 10 % evaluate only two environmental impact categories, including GHGs. This reflects a limited understanding of broader environmental impacts, with a predominant focus on CO_{2eq} emissions. When comparing different case studies, storage methods associated with the lowest emissions include metal hydrides and underground hydrogen storage. Another important observation is the trend of decreasing CO_{2eq} emissions as the storage system scale increases. Future studies should adopt more comprehensive approaches by analyzing a wider range of hydrogen storage technologies and considering multiple environmental impact categories in LCA. Moreover, it is crucial to integrate environmental, economic, and social dimensions of sustainability, as multidimensional assessments are essential to support well-informed, balanced decisions that align with the sustainable development of hydrogen storage systems.

1. Introduction

The need to reduce greenhouse gas (GHG) emissions to meet decarbonization goals by 2030 and to slow down the progression of climate change has driven governments, scientists, and society to pursue cleaner energy solutions. Among various renewable energy carriers, hydrogen is emerging as one of the most interesting global strategies for achieving decarbonization by 2050. It is the most abundant element on the planet, and its appeal as an energy carrier lies in its highly exothermic reaction with oxygen, which produces only water as a by-product. Hydrogen energy-to-weight ratio is notably higher than that of fossil fuels, with 1 kg of hydrogen (H_2) providing the same energy as 2.4 kg of methane (CH_4) or 2.8 kg of gasoline [1].

As of the end of 2021, hydrogen production remained heavily dependent on fossil fuels, with approximately 47 % of global hydrogen production derived from natural gas, 27 % from coal, 22 % from oil (as a by-product), and only about 4 % produced via electrolysis [2]. While fossil fuels still dominate hydrogen production, decarbonization policies are increasingly steering it away from these processes. In response, hydrogen production through water electrolysis, which generates only oxygen as a by-product and uses electricity from renewable sources, is gaining traction. The International Energy Agency (IEA) Net Zero Emissions by 2050 scenario [3] estimates that $ 41 billion will need to be invested in electrolyzer installations by 2030 to achieve decarbonization by 2025.

Building on this trend, according to the IEA *Global Hydrogen Review 2023* [4], the number of projects focused on low-emission hydrogen production is expanding rapidly. If all announced projects will be realized, annual hydrogen production could reach 38 Mt. by 2030, although 17 Mt. are linked to projects still in the early stages of development. The

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potential hydrogen production from these announced projects is now 50 % higher than it was at the time of the release of the IEA *Global* International Energy Agency *Hydrogen Review 2022* [4]. Governments around the world have adopted various policies to mandate and incentivize the use of low-emission fuels, such as hydrogen. In the European Union, this promotion is carried out through directives and regulations such as the Renewable Energy Directive (RED), the FuelEU Maritime Regulation, the ReFuelEU Aviation Regulation, as well as initiatives like the Hydrogen Bank and the Net Zero Industry Act. The RED is central to this effort, setting targets for low-emission fuels. The current version requires that by 2030, 14 % of the energy used in the transport sector must come from renewable sources. The 2023 amendment raises this target to 29 % and mandates that at least 1 % must come from renewable fuels of non-biological origin (RFNBOs), such as electrolytic hydrogen and e-fuels [5,6]. Additionally, the updated RED states that renewable hydrogen must account for 42 % of total industrial hydrogen consumption by 2030 and 60 % by 2035. In the United States, there are incentives at both the federal and state levels. Two main programs focused on hydrogen are the Clean Hydrogen Production Tax Credit (45 V) and California's Low Carbon Fuel Standard (LCFS). The 45 V, part of the Inflation Reduction Act (IRA), provides tax credits to hydrogen producers who meet defined carbon intensity (CI) thresholds. California's LCFS rewards fuels with a CI lower than the benchmark. Since 2022, the average LCFS credit value has been $ 91.27 per metric ton of CO_2 equivalent, reaching $566 in November 2024, depending on market fluctuations [6]. These programs highlight the crucial role of public policy in promoting low-emission fuels and enabling the economic viability of clean hydrogen.

However, the transition to a hydrogen-based energy system presents significant challenges to meet decarbonization targets, particularly in developing a supply chain for sectors where it has not yet been widely applied, such as heavy industry, transportation, fuel production, electricity generation and storage [7]. Nevertheless, several properties of hydrogen, such as its wide flammability range in air, extremely low boiling point, low ignition energy, and low volumetric energy density, combined with the lack of infrastructures for storage, transport, and distribution, pose major obstacles to its large-scale deployment and use in the current energy landscape [8,9]. Due to the unique characteristics of hydrogen, the development of efficient storage systems is essential, particularly considering the challenges related to safety, efficiency, and technical feasibility [10]. Each storage technology presents specific limitations. Storing hydrogen in liquid form or as compressed gas at high pressure allows for reduced storage volume, but still faces significant challenges regarding energy density, especially when compared to other fuels [11]. The lower volumetric energy density of hydrogen requires larger storage volumes per megajoule of energy, which in turn demands more robust, heavier, and costlier storage tanks [7]. On the other hand, solid-state storage using materials such as metal hydrides or porous structures like MOFs offers safety advantages due to their lower operational pressures and temperatures. However, these systems often face limitations related to overall weight and volume, as well as challenges in hydrogen adsorption and desorption kinetics [12,13].

Challenges addressed to make the development of a hydrogen economy feasible include not only techno-environmental issues, but all three dimensions of sustainability, namely social, environmental and economic. Indeed, decision-making with regard to the sustainability assessment of energy technologies is complex due to sometimes conflicting goals, such as low costs for end users, minimum environmental impact, security of supply, maximum social acceptance. Specifically, regarding hydrogen technologies, integrated studies covering all the three aspects of sustainability are missing [14]. Concerning techno-environmental issues, in nature hydrogen is not normally directly available in its pure form but is bound to other elements, requiring high energy expenditure for separation. Consequently, the environmental and energy performance of hydrogen energy systems strongly depends on the hydrogen donor and the energy source for the conversion process [15,16]. Comprehensive analyses are crucial to assess the suitability of hydrogen energy systems and to prevent the shifting of burdens across impact categories, or stages of the supply chain. Therefore, scholars are developing new theoretical frameworks to integrate impact factors of diverse nature [17,18].

To this purpose, three important methodologies can be utilized: Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social-Life Cycle Assessment (S-LCA). These analytical approaches are functional for evaluating and implementing the most sustainable hydrogen supply chains and can be integrated within a Life Cycle Sustainability Assessment (LCSA) [19]. LCA is a method used to analyze the environmental impacts of a product or a service, aiding in the selection of production methods that support a sustainable future in a low-carbon economy. When correctly applied, LCA can identify the stages of a process or service that significantly contribute to the product's environmental impact. One of the main applications of LCA is to provide technical support for the development of decarbonization policies and the adoption of low environmental impact technologies. In this context, several hydrogen incentive programs include, among their criteria, the quantification of environmental impacts through LCA, aiming to guide the selection of the most effective and sustainable technological pathways for implementation [6]. LCC is a methodology used to account for all costs associated with a product. It is also widely utilized as a tool to identify cost hotspots within products or projects, demonstrating the system's economic viability [20]. Although this is a highly relevant topic in the literature, due to the presence of other reviews focused on the economic feasibility of hydrogen storage, this aspect will not be specifically addressed in the present study. S-LCA is a methodology developed to assess the positive and negative social and socio-economic impacts of a product throughout its life cycle [21]. S-LCA is primarily based on the ISO 14040 standard for environmental LCAs. Nevertheless, the United Nations Environmental Program has additionally updated the dedicated S-LCA guidelines, with the objective of refining and standardizing the methodology regarding potential social impacts [22]. These include six categories of stakeholders: workers, local community, value chain actors, society, consumers, and children. Each stakeholder category is associated with a set of impact subcategories. These subcategories represent socially relevant issues that may affect the people involved in the system under analysis. Nonetheless, there is ongoing work to develop methodological recommendations for conducting rigorous S-LCAs of hydrogen-related systems [23]. This undertaking is rendered challenging by the limited level of readiness and deployment at scale of these technologies. It is worth considering that the social assessment of hydrogen storage systems is not the focus of any of the existing literature and the S-LCA studies of green hydrogen were not sufficiently numerous to be included in the literature review in order to provide a meaningful overview of the data obtained and, consequently, suggestions on the social implication of the hydrogen storage use [23,24].

This work is focused on LCA, which allows for the development of new strategies to make the production more sustainable [25]. The rules and requirements for LCA are defined by international standards ISO 14040 and ISO 14044. ISO 14040 addresses the principles and framework of LCA, while ISO 14044 provides detailed requirements and guidelines. LCA is structured into four stages: (1) Goal and Scope Definition; (2) Inventory Analysis; (3) Impact Assessment; and (4) Interpretation of Results. In this context, this study aims to review LCA related to hydrogen storage, given that other research has already evaluated the results of LCA in hydrogen production [26,27]. The focus is on identifying areas for improvement in these systems and the most effective solutions found in existing studies. The approach for this review is to identify, analyze, and map the existing body of research that applied LCA to energy storage systems that utilize hydrogen as an energy vector. Although other forms of hydrogen storage can be considered, such as Liquid Organic Hydrogen Carrier (LOHC) systems, composed of pairs of organic compounds in hydrogen-lean and hydrogen-rich states, such as ammonia and methanol [28], this modality will not be addressed in this study, which focuses on hydrogen as an energy vector for storing renewables. By reviewing and synthesizing these studies, we aim to provide a comprehensive understanding of the current landscape, highlight gaps in the research, and offer insights into the environmental impacts associated with hydrogen-based energy storage technologies. Additionally, the study highlights gaps that need further investigation to provide a comprehensive overview of the various technologies applied to hydrogen storage, from environmental perspectives. The existing body of literature on S-LCA studies of green hydrogen is, at present, only in its infancy. In fact, the majority of studies focus on hydrogen production or electrolyzer and fuel cells. To the best of our knowledge, there is no S-LCA of hydrogen storage. For this reason, we have not included a literature review of hydrogen S-LCA in this work.

2. Literature analysis

To understand the current state of the research on energy storage in the form of hydrogen, we identified the number of relevant articles using a suitable research tool. To identify relevant LCA studies on hydrogen storage technologies, an initial search was performed using the SCOPUS database, Fig. 1 presents the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework.

The search results were refined by limiting them to English-language articles published in peer-reviewed scientific journals, ensuring that the selected literature was both relevant and accessible, obtaining a refined set of 147 articles. A manual skimming process was then undertaken, where only studies that specifically employed case study of LCA to evaluate hydrogen storage systems or to compare various energy storage systems (with hydrogen storage being one of the options) were selected. This process resulted in the final selection of 30 relevant articles, which were included in the review.

3. Life Cycle Assessment

It is important to consider the sustainability and carbon neutrality of hydrogen systems to ensure that their deployment contributes effectively to the overall goals of the energy transition. Although hydrogen is a clean and environmentally friendly fuel, the production methods can result in different levels of environmental impact [29]. LCA are employed to evaluate the overall environmental performance of hydrogen systems, encompassing the entire supply chain from production to end use. These assessments offer valuable insights into the carbon footprint, energy consumption, and other environmental indicators linked to hydrogen production and utilization [26].

In this context, several LCA studies have been conducted across different segments of the hydrogen supply chain to evaluate the environmental performance of proposed solutions and to identify areas for improvement. Fig. 2 presents a cluster map of keywords from retrieved articles using the Scopus tool with the search terms {“Hydrogen”} and {“Life Cycle Assessment,” or “LCA”}. The size of each cluster reflects the number of articles associated with that keyword.

The cluster related to hydrogen production is approximately the same size as the one for LCA, whereas the cluster for energy storage is significantly smaller. This suggests that, compared to other topics, there are relatively few LCA studies conducted on energy storage, indicating that this area is underexplored. Given that hydrogen storage is a critical component in the development and implementation of the hydrogen supply chain, further research in this area is essential. Indeed, the optimal solution is highly dependent on the scale and specific boundary conditions of each application, which must be clearly defined for both renewable energy production and storage. Therefore, developing a

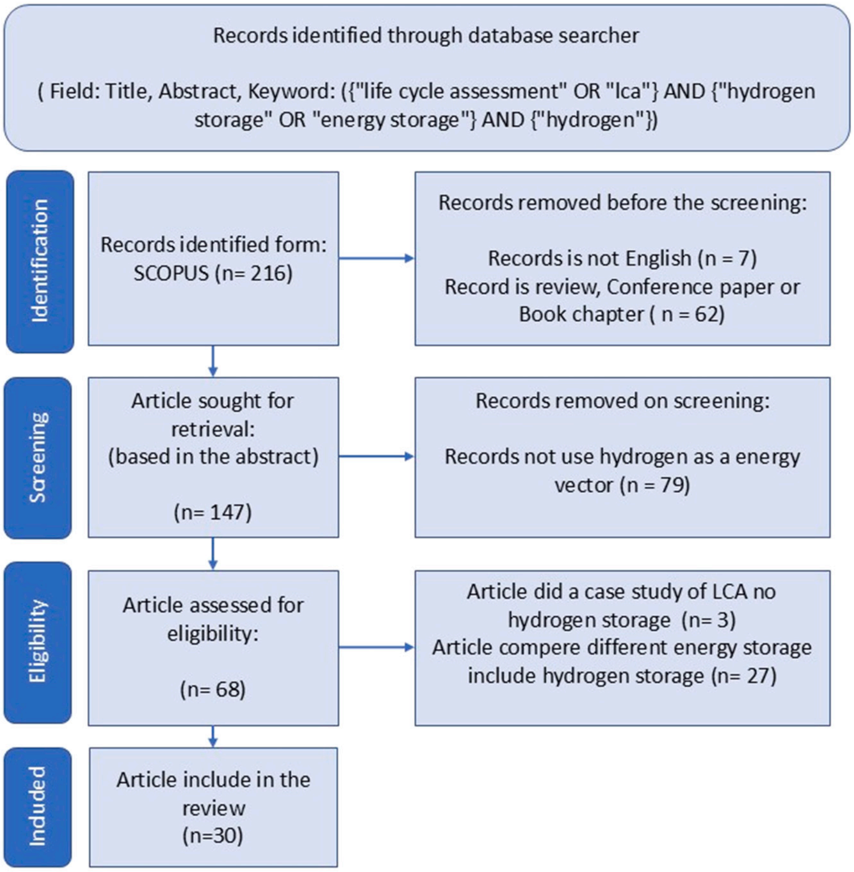

Fig. 1. The PRISMA framework outlining the criteria used for article selection in this review.

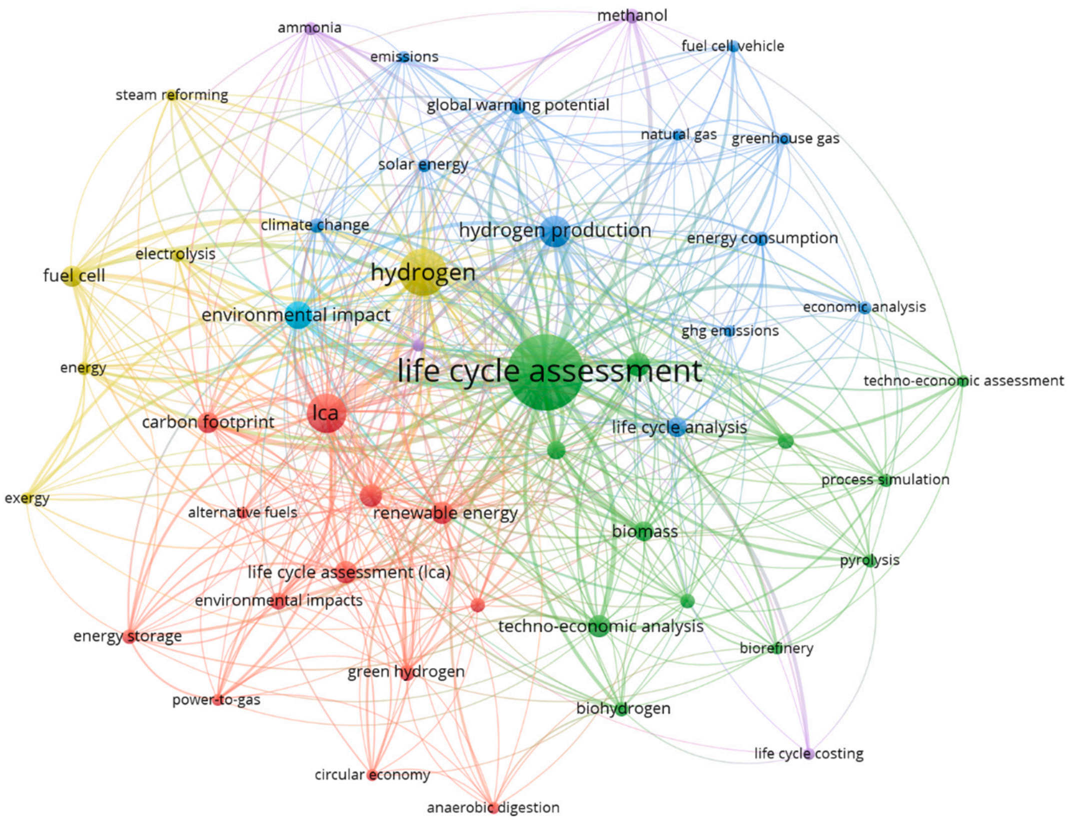

Fig. 2. Cluster map of keywords from articles retrieved using the Scopus tool with the search terms {“Hydrogen”} and {“Life Cycle Assessment,” or “LCA”}.

comprehensive database of case studies could serve as a foundational basis for establishing general strategies [30].

As previously explained, only studies that employed LCA to evaluate hydrogen storage systems or to compare various energy storage systems, with hydrogen storage as one of the options, were selected for this review. The selected articles included in this study are presented in Table 1. An important observation is that 33 % of these articles only analyze GHG emissions, while 10 % examine just two environmental impacts, with one of them being CO_{2eq} emissions. Studies that analyzed a broader range of impacts emphasize the importance of examining multiple aspects across four main impact categories, as certain technologies have a high impact on specific categories [31,32]. Focusing on a single impact, such as CO_{2eq} emissions, is insufficient to grasp the overall environmental performance of the system. The exclusive focus on Global Warming Potential (GWP) overlooks other critical environmental impacts, such as human toxicity, related to the adverse effects of chemical substances on public health, or resource depletion, which involves the excessive consumption of minerals, rare metals, water, and non-renewable energy. Technologies with low carbon emissions may require large amounts of natural resources. As demonstrated by Le et al. [31], the complete replacement of energy from fossil sources with renewable sources in an energy production and storage system resulted in burdens across several impact categories, including ozone layer depletion, particulate matter formation, acidification, eutrophication in all its subcategories, and the use of fossil, mineral, and metal resources. This limited approach, therefore, may favor solutions that, while appearing environmentally advantageous from a climate perspective, end up with shifting impacts to other equally important environmental categories. Thus, to ensure a truly sustainable analysis and to support well-informed technical and policy decisions, it is essential that LCA incorporates multiple impact categories in an integrated and comprehensive manner.

A recurring characteristic observed (Table 1) in the evaluated studies is the predominant adoption of cradle-to-use approaches, with 54 % of the works not including the End-of-Life (EoL) phase. Although LCA is, by definition, a methodology that considers all stages of the life cycle of a product, process, or service, there is a clear tendency to omit this final phase in many studies. This limitation can be attributed to several factors. Firstly, there is a notable lack of reliable data regarding the final destination of products, which generates high uncertainty in the modeling of disposal scenarios. As highlighted by Fischer et al. [33], this uncertainty often leads to excessive simplification of EoL models, compromising the robustness of the results. Furthermore, there is no clear methodological consensus, either in standards or in reference guidelines, on how to appropriately model this phase in LCA [34]. The additional complexity of incorporating the EoL phase, combined with the lack of consistent data and guidelines, often discourages researchers from including it, especially in studies that are already complex due to raw material extraction and use stages. However, this omission can significantly compromise the completeness of the analysis, particularly in renewable energy systems, where the consumption of raw materials tends to be high, making the disposal phase even more relevant to the overall results [35].

Fig. 3 illustrates the different technologies examined in selected studies for hydrogen storage. It is evident that the majority is focused on storing hydrogen in gas tanks compared to other technologies, even if several other strategies are taken into consideration. The widespread presence of studies on hydrogen storage in the form of compressed gas is due to the fact that this is the most established and widely adopted method in industrial practice. It is a mature technology that offers high efficiency in hydrogen charging and discharging processes, which is a key aspect for energy storage systems [63].

The second most studied hydrogen storage method is as a solid in metal hydrides. The solid state storage is based on the ability of certain metals and metal alloys (such as magnesium, nickel, and titanium) to absorb hydrogen under low pressure and moderate temperature

Table 1
List of hydrogen-focused LCA articles selected for the literature review.

Reference	Description/ goal	System boundary[a]	Functional unit	Energy source	Hydrogen storage	Methodology	Impact category	Purposes for energy storage
Agostini et al. [36]	LCA of different hydrogen storage system	Cradle-to-grave	1 kWh energy stored	–	Metal hydride Gas tank	–	Global Warming Potential, Abiotic Depletion Potential, Acidification, Freshwater eutrophication, Marine eutrophication	Energy storage for terrestrial transport
Altea et al. [37]	Surplus electrical energy in the Brazilian power grid	Cradle-to-use	2.78×10^{-4} kWh energy produced	Surplus electricity in Brazil's power grid	Gas tank	–	Non-Renewable Unit Exergy Cost, Total Unit Exergy Cost, CO_{2eq} emission cost	Storage of renewable energy
Belmonte et al. [30]	LCA of different energy storage system	Cradle-to-use	3 kW power	Solar energy	Gas tank	IPCC	Global warming potential	Power supply to a building
Belmonte et al. [38]	Energy storage for stationary and mobile applications	Cradle-to-use	1 kW power	Solar energy	Gas tank	IPCC	Global warming potential	Hydrogen storage assessment
Benitez et al. [39]	Energy storage in the car	Cradle-to-grave	Impact per km traveled	German electricity mix	Gas tank	ReCiPe 2016	Climate change, Ionizing radiation, Fossil depletion, Terrestrial ecotoxicity, Human toxicity	Energy storage for terrestrial transport
Bionaz et al. [40]	Power supply to a remote location	Cradle-to-grave	1 MWh energy produced	Renewable energy	Gas tank and batteries	IPCC	Global warming potential	Supply for remote locations
Florio et al. [41]	Energy storage for house	Cradle-to-use	1 kWh energy produce	Gas natural Solar energy	Gas tank Natural gas	ReCiPe world 2016 IPCC 2013 GWP 100a	All the impact categories of ReCiPe	Power supply to a building
Fiaschi et al. [42]	Energy storage to an energy system	Cradle-to-use	1 MWh energy produced	Solar energy	Gas tank	ReCiPe world 2016 MidPoint	Global warming potential, Acidification potential, Human toxicity potential, Particulate matter formation, Photochemical ozone formation	Storage of renewable energy
Gandiglio et al. [43]	Power supply to a remote location	Cradle-to-grave	1 kWh of energy produced	Solar energy	Metal hydride and batteries	Environmental Footprint	Climate change, Ozone depletion, Photochemical ozone formation, Particulate matter, Acidification, Eutrophication - Freshwater, Eutrophication - Marine, Eutrophication - terrestrial, Ecotoxicity - Freshwater, Resource use - fossil, Resource use - Minerals and metals	Power supply for remote locations
Garraín et al. [44]	Energy storage for a portable device	Cradle-to-use	Useful life of the fuel cell	Spanish electricity mix	Metal hydride	Environmental Footprint	All the impact categories of EF	Hydrogen storage assessment
Groppi et al. [45]	Power supply to a remote location	Cradle-to-use	–	Solar energy	Gas tank Batteries and gas tank	–	CO_{2eq} emission	Power supply for remote locations
Jiao and Månsson [46]	Energy storage to an energy system	Cradle-to-grave	1 kWh energy stored	Solar and wind energy	Gas tank	IPCC	Global warming potential	Storage of renewable energy
Katsigiannis et al. [47]	Energy storage to an energy system	Cradle-to-use	1 kWh energy produced	–	Gas tank	IPCC	Global warming potential	Storage of renewable energy
Konrad et al. [48]	Energy storage in the car	Cradle-to-grave	1 kWh energy produced	Austrian energy mix Renewable energy	Gas tank	IPCC	Global warming potential, Energy demand	Energy storage for terrestrial transport
Le et al. [31]	Power supply to a building	Cradle-to-grave	1 kWh energy produced	Solar energy	Batteries and gas tank	Environmental Footprint	Climate change, Ozone depletion, Photochemical ozone formation, Particulate matter, Acidification, Eutrophication – Freshwater, Eutrophication - Marine, Eutrophication - terrestrial, Ecotoxicity - Freshwater, Resource use - fossil, Water use, Resource use - Minerals and metals	Power supply to a building

(*continued on next page*)

Table 1 (*continued*)

Reference	Description/ goal	System boundary[a]	Functional unit	Energy source	Hydrogen storage	Methodology	Impact category	Purposes for energy storage
Mostert et al. [49]	Energy storage to an energy system	Cradle-to-use	14.60 MWh	Renewable energy	Gas tank	IPCC	Global warming potential	Storage of renewable energy
Naumann et al. [50]	Power supply to a building	Cradle-to-grave	4 MWh (heat produced) and 2350 kWh (energy produced)	Solar energy	Gas tank	Environmental Footprint	All the impact categories of EF	Power supply to a building
Oliveira et al. [51]	Energy storage for an energy grid	Cradle-to-grave	1 MWh energy produced	Belgium electricity mix Wind energy Solar energy	–	ReCiPe 2008	Climate change, Human toxicity, Particulate matter formation, Fossil depletion	Storage of renewable energy
Ozbilen et al. [52]	Energy storage to an energy system	Cradle-to-grave	1 kWh energy produce	UCTE 2004 Wind energy Hydro energy	Gas tank	CML 2001	Global warming potential	Storage of renewable energy
Peppas et al. [53]	Power supply to a building	Cradle-to-use	1.47 kWh energy produce	Greek energy grid mix	Gas tank	CML 2001 ReCiPi 2008	Acidification Potential, Global warming potential Photochemical oxidant formation	Power supply to a building
Qi et al. [54]	Power supply to a building	Cradle-to-grave	–	Solar energy	Gas tank	Eco-indicator 99 impact adapted	Single score	Power supply to a building
Roes and Patel [55]	Hydrogen storage in the car	Cradle-to-use	4.1 kg H2 stored	–	Gas tank Metal hydride Cryogenic tank Metal organic framework	–	Depletion of fossil, Global warming potential	Energy storage for terrestrial transport
Rossi et al. [56]	Energy storage for house	Cradle-to-grave	1 MWh energy produced	Solar energy	Gas tank	ReCiPe 1.1 (2014)	Ecosystems-total, Human Health- total, Resources -total	Power supply to a building
Teng et al. [57]	Energy storage in to bus	Cradle-to-use	1 kg of H2 stored	–	Gas tank	–	CO_{2eq} emission	Energy storage for terrestrial transport
Tschiggerl et al. [58]	Hydrogen storage assessment	Cradle-to-use	0.28 kWh energy produced	Wind and solar energy	Underground gas storage	CML	Acidification, Depletion of abiotic resources, Eutrophication - Freshwater ecotoxicity, Global warming potential, Human toxicity, Photo-oxidant formation, Resource Depletion, Stratospheric ozone Depletion	Hydrogen storage assessment
Valente et al. [59]	Energy storage to an energy system	Cradle-to-use	1 MWh energy produced	Hydro energy	Metal hydride	CML method	Abiotic depletion, Acidification, Eutrophication, Ozone layer depletion, Land competition, Photochemical oxidant formation, Global warming potential, Cumulative non-renewable energy demand, Cumulative total energy demand	Storage of renewable energy
Viole et al. [60]	Power supply to a remote location	Cradle-to-grave	7.7 GWh (energy produced per year)	Solar energy Diesel	Gas tank Batteries	Environmental Footprint	Depletion of mineral resources, Water use, Climate change	Power supply for remote locations
Viole et al. [61]	Power supply to a remote location	Cradle-to-grave	7.7 GWh (energy produced per year)	Solar energy Diesel	Gas tank Batteries	Environmental Footprint	Depletion of mineral resources, Water use, Climate change impact	Power supply for remote locations
Wevers et al. [32]	Energy storage to an energy system	Cradle-to-use	1 kWh energy produced	Renewable energy Natural gas	Underground gas storage	ReCiPe 2016	Climate change, Photochemical ozone formation, Particulate matter formation, Terrestrial acidification, Marine eutrophication, Mineral resource scarcity, Fossil resource scarcity	Storage of renewable energy
Ye and Lu [62]	Energy storage in the car	Cradle-to-use	–	–	Gas tank Cryogenic tank	CML-IAdatabasever.2016	Climate change	Energy storage for terrestrial transport

[a] Cradle-to-grave = the life cycle impacts from raw material extraction (cradle) through disposal (grave). Cradle-to-use = the life cycle impacts from raw material extraction (cradle) through use phase (use), the disposal phase is not evaluated.

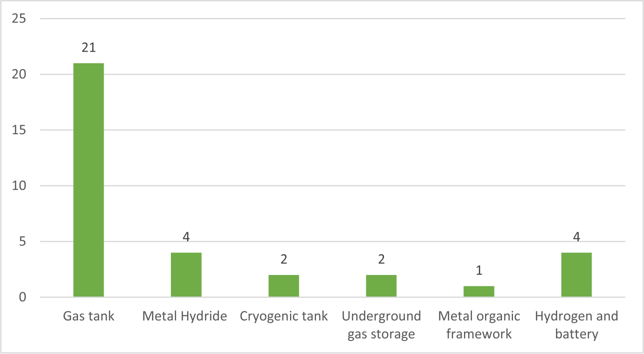

Fig. 3. Number of articles of LCA each hydrogen storage system studied.

conditions, forming solid hydrides compounds. Hydrogen is released upon heating the material under reduced pressure. Since the hydrogen is chemically incorporated into the crystalline structure of the metal, it can be stored safely without the need for extremely high pressures or cryogenic temperatures. Due to these characteristics, metal hydrides stand out as one of the safest hydrogen storage alternatives [13,63].

Hydrogen storage in liquid form is rarely addressed in the literature, with only two studies identified. This limitation is linked to significant technical and energy-related challenges. Liquid hydrogen requires highly specialized cryogenic systems capable of maintaining extremely low temperatures, around 21 K [64]. Additionally, the liquefaction process consumes a substantial portion of the fuel's own energy. In fact, up to 35 % of hydrogen's energy content may be used solely for liquefaction and maintaining its liquid state [11]. These demands directly impact the Energy Return on Energy Invested (EROI), defined as the ratio between the net energy produced and the total energy invested in the system [65]. The resulting low EROI and the high costs associated with effective thermal insulation make liquid hydrogen a technically challenging and economically less attractive option, which may explain the limited interest and low number of studies dedicated to this technology.

Another strategy that has been not extensively explored is underground hydrogen storage, with only two studies evaluating this technology. Underground gas storage involves the artificial creation of reservoirs within deep geological formations, where gas is stored in two forms: working gas (injected and withdrawn according to demand) and cushion gas (permanently retained to maintain minimum pressure and prevent water intrusion). Underground hydrogen storage follows principles similar to those used for natural gas and carbon dioxide (CCS). Its main advantages include enhanced safety, efficient land use, and economic viability especially when compared to above-ground storage tanks. [66].

Hydrogen storage using metal-organic frameworks (MOFs) remains underexplored in Life Cycle Assessment (LCA) studies, with only one identified to date. MOFs are crystalline materials characterized by high porosity and surface area, enabling efficient hydrogen adsorption through van der Waals forces. Although promising, their large-scale application is limited by challenges such as moisture sensitivity, structural instability, and low electrical conductivity. Enhancements through metal doping, nanoparticle incorporation, and cryo-adsorption strategies may improve performance, particularly under ambient temperature and moderate pressure conditions [12].

The combination of different technologies of hydrogen storage and battery is a really well-developed approach, and can help reduce the CO_{2eq} emission of energy equipment.

Selected articles of LCA in hydrogen storage were classified according to their specific purposes for energy storage. The first category, ***Hydrogen Storage Assessment***, includes studies focused on the life cycle assessment of various hydrogen storage systems. The second category, ***Energy Storage for Terrestrial Transport***, addresses the storage of hydrogen directly in vehicles or at refueling stations. The ***Power Supply for Buildings*** category encompasses research on energy storage systems intended to provide power to residential or commercial buildings, typically utilizing renewable energy in off-grid configurations. ***Power Supply for Remote Locations*** evaluates the implementation of renewable energy solutions to supply power in remote areas that currently depend on diesel fuel. Finally, ***Storage of Renewable Energy*** category includes studies on hydrogen storage solutions for renewable energy production facilities, which are necessary to manage intermittency and maintain grid stability. It also encompasses the storage of excess energy generated within a national grid to be used during periods of supply shortage. The categories are organized in ascending order according to the system's storage capacity. The following sections provide a more detailed overview of the categories of hydrogen storage.

Table 2 presents the distribution of LCA studies according to the specific purposes of hydrogen-based energy storage. It is observed that only three articles focus exclusively on hydrogen storage, while the remaining studies consider hydrogen as one of several options within broader energy storage systems. The categories with the highest number of publications were *Renewable energy storage* and *Power supply to buildings*, both associated with stationary applications, although differing in system scale. Overall, there is a predominance of studies addressing stationary uses of hydrogen, with exceptions found only in the categories *Hydrogen storage assessment* and *Energy storage for terrestrial transport*, in which, in some cases, hydrogen is stored in stationary systems and subsequently used to recharge electric vehicles. This trend is closely linked to technical and economic limitations associated with mobile hydrogen applications, particularly due to its low volumetric energy density and the need for robust and heavy storage systems. Although technologies such as Type IV tanks, which withstand pressures up to 70 MPa and offer a high strength-to-weight ratio, are recommended for mobile applications using compressed hydrogen gas (CGH_2), it is estimated that up to 15 % of hydrogen's energy content is consumed during compression, reducing system efficiency [11]. In light of these factors, the reviewed studies indicate a greater technical feasibility for hydrogen in stationary applications, reflecting its preferential adoption in such contexts.

3.1. Hydrogen storage assessment

Storing hydrogen is a challenge in establishing a new supply chain for its use as an energy carrier. This challenge is primarily due to hydrogen low density, high volatility and flammability [9]. Gas storage systems require large volumes, which often necessitate storing hydrogen under high pressure or in liquid form, both of which involve significant energy consumption to achieve the necessary hyperbaric pressures and cryogenic temperatures [13]. Other storage technologies can be utilized, including metal hydrides, underground gas storage, blending hydrogen

Table 2
Number of studies on hydrogen handling categorized by their specific energy storage purposes.

Category	No. of article
Hydrogen storage assessment	3
Energy storage for terrestrial transport	6
Power supply to a building	7
Power supply for remote locations	5
Storage of renewable energy	9

with natural gas, or converting it into other molecules such as ammonia or methane [67]. To assess environmental performance and identify areas for improvement, various hydrogen storage technologies were evaluated. This section presents articles evaluating hydrogen storage systems without a specific application. Fig. 4 presents a schematic overview of the hydrogen storage strategies examined in this section, including gas compress, metal hydrides and underground, as well as the energy sources utilized for hydrogen production.

In Garraín et al. [44] the environmental impact evaluation study was conducted on an integrated system including a hydrogen storage prototype integrated with a portable fuel cell, which uses a metal hydride with the $LaNi_5$ composition. This device is proposed as an alternative to batteries, which are widely used in portable energy storage systems. The analysis reveals that the greatest contribution to the environmental impacts of the integrated system comes from the hydrogen supply and storage processes. Additionally, it highlights the importance of the energy source used in hydrogen production, which in the analyzed case is based on Spain's energy mix, which still relies on some fossil fuel technologies. In the manufacturing process of the fuel cell, the anode plates emerge as the main factors contributing to the device environmental footprint.

Belmonte et al. [38] investigated two alternative energy storage systems: lithium-ion batteries and hydrogen storage, both integrated with proton-exchange membrane (PEM) fuel cell technologies. These two technologies have been analyzed for both stationary and mobile applications. Specifically, the stationary application involved a single-family residence designed to provide two days of self-sufficiency, while the mobile application focused on a drone with a flight time of 120 min. The battery system demonstrated the best performance for mobile applications, with a significantly lower cost compared to the hydrogen storage system, which is approximately twice as expensive for solutions of the same size and purpose. Additionally, the GWP of the hydrogen system is about three times higher than that of the battery-based system. In contrast, for stationary applications, the battery system has disadvantages regarding cost, as it is about 15 % higher than the hydrogen system. However, the GWP of the hydrogen system remains higher, indicating a greater environmental impact.

A promising strategy for hydrogen storage is the utilization of caves, as detailed in an analysis of the environmental impacts of this renewable energy storage technology in the form of gas within porous spaces of geological formations [58]. The stored gases include hydrogen produced by electrolysis and methane. Hydrogen is generated, compressed along with natural gas, stored underground, and subsequently dried for use as fuel. However, the high concentration of hydrogen in these spaces can lead to various impacts with different levels of safety risk. One approach to mitigate this risk is blending hydrogen with other gases, thus reducing the partial pressure [68]. Results on environmental impacts primarily depended on the energy source, for its handling while all other input and output flows analyzed, linked to various process units such as synthesis and storage, were found to be of less relevance. Results indicated the contribution of the hydrogen plant to the total environmental burden and energy demand. Including required energy, compression, storage (porous space reservoir), free water removal, and glycol dehydration, depend on the type of gas used and the energy source for obtaining hydrogen. The contributions of storage and processing after storage demonstrated a low impact. Additionally, the main source of energy consumed and the specific efficiency of these processes were identified as the most critical parameters to be considered.

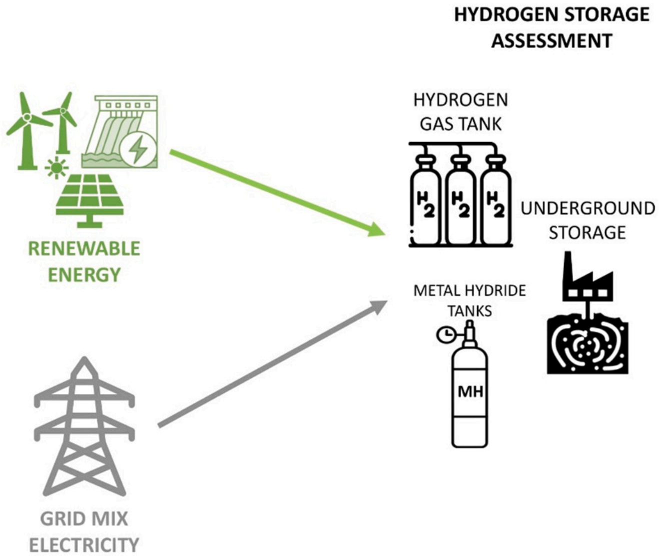

Fig. 4. Diagram illustrating hydrogen storage technologies analyzed in LCA studies in the section "Hydrogen storage assessment", along with the energy sources used to produce hydrogen.

3.2. Energy storage for terrestrial transport

Electric vehicles are an important technology for decarbonizing road transport, a sector responsible for over 15 % of global energy-related emissions [69]. In recent years, the sale of electric vehicles is increased significantly, and electric cars accounted for around 18 % of all cars sold in 2023 [70]. Hydrogen offers an effective solution for seasonal energy storage and plays a key role in integrating the electricity and mobility sectors [71]. With a focus on the use of hydrogen in electric vehicles, various hydrogen storage methods were evaluated, along with an assessment of their environmental impact. Fig. 5 represents the primary strategies for hydrogen storage assessed in LCA studies related to terrestrial transport.

The environmental impacts associated with hydrogen storage in solid-state (HSS), employing an advanced storage system composed by metal hydrides and complex hydrides, interconnected in an 6061Aluminum alloy tank, were assessed in comparison with two types of high-pressure storage tanks: type III (350 bar) and type IV (700 bar). These storage systems supply hydrogen to fuel cells acting as an APU (Auxiliary Power Unit) for a vehicle [36]. The material inventory revealed that a prototype tank based on solid-state hydrogen storage materials requires a greater amount of materials for its construction compared to commercially available type III and IV pressurized gas tanks. For all the impacts analyzed - Global Warming Potential, Abiotic Depletion Potential, and Primary Energy Demand, renewable and non-renewable - a high contribution of structural materials, mainly steel, was observed in pressurized gas tanks systems. However, the analysis did not consider the disposal of storage systems, but the recycling of materials used in construction may considerably reduce the overall impacts. Regarding climate change, the energy saved during the operation of HSS systems almost entirely offsets the additional emissions during the construction phase of the HSS system, due to the energy used for gas compression coming from the electrical grid, which has a small share of renewable energy. However, with a future energy mix less dependent on fossil fuels, the CO_{2eq} savings during HSS operation are not sufficient to offset the higher emissions from construction. Additionally, when considering the electricity needed for compression, primary energy consumption is slightly lower for HSS systems compared to type III and type IV tanks.

Another environmental impact evaluation study was conducted using type III and IV tanks for storing hydrogen as a gas under high pressure in comparison to storing hydrogen in liquid form using cryogenic tanks, with the aim of providing energy to a sedan vehicle [62]. Results showed that, over the life cycle, type IV high-pressure tanks emit fewer greenhouse gases, with 5539 kg of CO_{2eq}, compared to type III high-pressure tanks, with 7219 kg of CO_{2eq}, and cryogenic tanks, with 135,000 kg of CO_{2eq}. In the case of the cryogenic storage tank, 98 % of CO_{2eq} emissions occur during the storage process, due to the need for

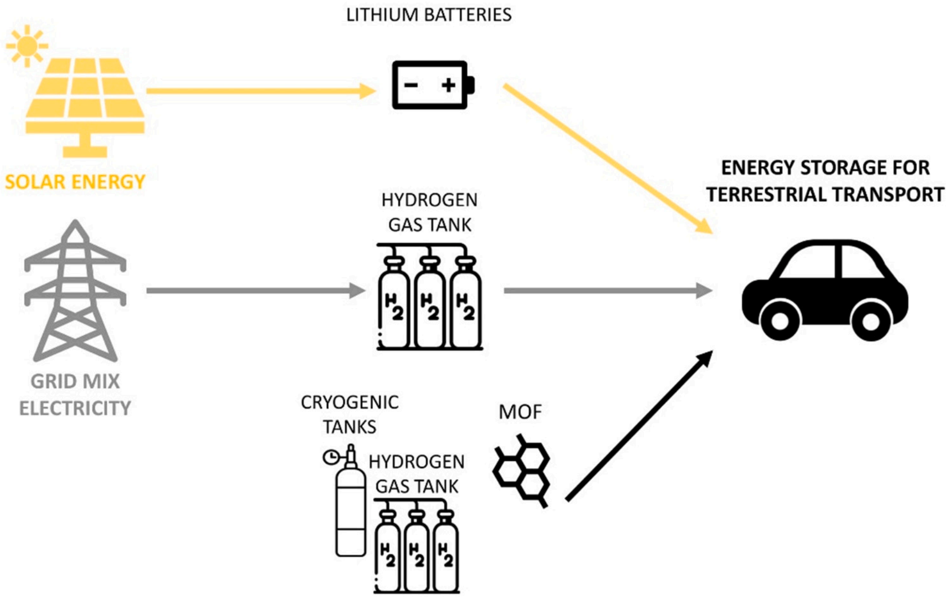

Fig. 5. Diagram illustrating the source of energy used to produce hydrogen and the hydrogen storage systems analyzed in LCA studies in the section "Energy storage for terrestrial transport".

energy to keep the gas in its liquid phase at low temperature.

The use of a type IV carbon fiber tank to provide hydrogen to power a fuel cell in a vehicle designed for five passengers was analyzed by Benitez et al. [39]. It encompasses all the components required to apply this technology to a vehicle, including the hydrogen tank, fuel cell, battery, electrical system, and chassis. Two different scenarios were evaluated: one using the technology available at the time of the study (2021) and another based on projected technology for 2050. Across various impact categories, the 2050 scenario showed better performance, primarily due to the anticipated energy mix, which is expected to reduce the environmental impact at every stage. The analysis evaluated also the environmental impacts of raw materials in vehicles, such as carbon fiber in the tank and platinum in the fuel cell. Vehicles production accounted for 66 % of greenhouse gas emissions and 87 % of human toxicity impact. The environmental impacts of the hydrogen tank were compared to those of the chassis and fuel cell. While the tank was the largest contributor to climate change, ionizing radiation, and fossil fuel depletion, it had a smaller role in human toxicity and ecotoxicity, where the fuel cell was the primary contributor. A future scenario showed improved tank performance, especially for climate change, reducing emissions from 15 kg of CO_{2eq} per 100 km to 9 kg.

Different hydrogen storage options for a fuel cell car within a driving range of 450 km were investigated [55]. Four hydrogen storage technologies have been analyzed: compressed hydrogen, liquid hydrogen, metal-organic frameworks (MOF) and metal hydrides. The study shows that hydrogen compression and liquefaction result in significantly higher environmental impacts, compared to storage in metal hydrides or MOF. The high reusability of metal hydrides and MOF contributes to these systems having lower environmental impacts. In addition, compressed and liquid hydrogen systems require a high quantity of energy for their operation, which increases their environmental impacts.

Another analysis focused on the use of electric buses powered by various fuel technologies, including batteries, fuel cell powered by H_2, and internal combustion [57]. For the system using hydrogen as fuel, the study encompassed the entire process, from hydrogen production, transportation, and refueling to the manufacturing of the storage system and the operation of buses in two different cities, taking into account routes of varying distances. When comparing the different energy storage, fuel cell buses stood out for having the lowest carbon emissions, despite their higher energy consumption.

Konrad et al. [48] evaluated the environmental impact of using hydrogen to recharge electric vehicles in Vienna was evaluated using a prototype of the MHP (Mobile Hydrogen Power Supply). CO_{2eq} emissions were assessed across various hydrogen production methods: coal gasification, steam methane reforming (with and without carbon capture), electrolysis from wind, solar, and hydro energy, and biomass gasification. Different production and transport scenarios were tested. The lowest GWP and cumulative energy demand were observed in the biogas route, with 2.27 kg CO_{2eq}/kg-H_2 and 63.04 kWh/kg-H_2, respectively. Decentralized hydrogen production, like electrolysis and biogas, reduced environmental impact by minimizing transport. The hydrogen supply route significantly influenced GWP during the use phase, making production and end-of-life processes more critical, while the supply route has lower GWP, as with Austria electric grid or biogas.

3.3. *Power supply to a building*

Integrating renewable energy into the construction sector, particularly through solar energy, offers an innovative and sustainable approach to decentralization power generation. Given the intermittent nature of solar energy and its lower output during winter, when energy demand is highest, storing excess energy for later use becomes highly advantageous [45]. This not only reduces dependence on the electricity grid, which in many countries still relies significantly on fossil fuels [72], but also enhances energy resilience. Various configurations were evaluated to assess the effectiveness of this approach, including the incorporation of hydrogen storage. Fig. 6 illustrates the technology for hydrogen storage that are analyzed in LCA studies focused on power supply to buildings.

Residential energy supply was investigated in two renewable energy storage systems applied to a family residence in Italy, addressed from different perspectives [30]. The main distinction between the two systems lies in the storage method: in one, energy is stored in lithium batteries, while in the other, hydrogen is produced by an electrolyzer and stored in cylinders at 30 bar, later consumed by a fuel cell. The two systems differ in terms of sizing. The hydrogen storage-based system requires a greater number of solar panels due to the energy demand for electrolysis. LCA results suggested that both devices appear to have smaller impacts than other system components, such as solar panels and gas cylinders. Although not mentioned by the authors, it is important to

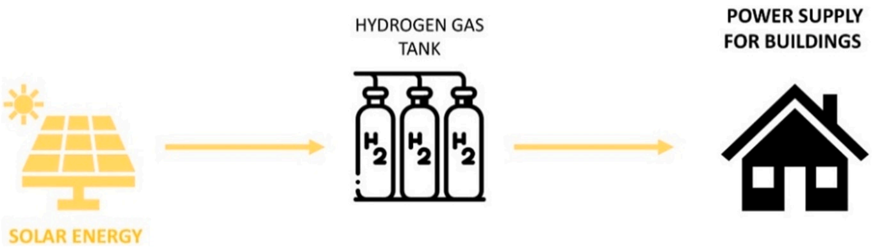

Fig. 6. Diagram illustrating hydrogen storage systems analyzed in LCA studies in the section "Power supply to a building". Solar energy was used in all assessments in this section to produce hydrogen.

note that cylinder storage demonstrated lower environmental performance compared to battery use.

The partial replacement of energy supply from the electrical grid with solar energy in a three-story building was evaluated, considering that the renewable energy system installed in the building includes photovoltaic panels, along with energy storage in a hybrid system composed of batteries and hydrogen in gas tank [31]. This energy is then directed to provide electricity, with an additional fraction coming from the municipal electrical grid. The amount of energy from the electrical grid varies as the system aims to become increasingly renewable and energy self-sufficient (SSR), ranging from 80 % to 100 %. In terms of climate change or CO_{2eq} emissions, the highest impact of 0.22 kg CO_{2eq}/kWh observed at the lowest SSR of 80.81 %. As the SSR increased to 96.20 %, the impact dropped to its lowest value of 0.15 kg CO_{2eq}/kWh. However, as the SSR continued to increase (i.e., the building approaches self-sufficiency), the environmental impact increased significantly, reaching 0.19 kg CO_{2eq}/kWh at an SSR of 99.44 %. Beyond this threshold, a rapid increase in component size was observed, leading to a larger carbon footprint. When considering other impact categories, results indicated that achieving a very high SSR may requires significant resource inputs, resulting in increased environmental impacts, that may not offset the benefits of renewable energies in many impact categories.

In Naumann et al. [50], the supply of energy and heat to a residence using solar energy was tested with three different systems. The primary system was a Solar-Hydrogen Systems (SHS), for which a photovoltaic (PV) system serves as the energy source. The energy produced is supplied to the residence, once the household energy demand is met, any unused electricity was stored in a lithium-ion battery. If the PV system energy supply was no longer sufficient to cover the load, the stored energy from the battery can be fed back into the system. When the full storage capacity of the battery was reached, and the electricity generated by the PV system still exceeds the household current consumption, the excess energy was used to produce hydrogen, then stored in a gas tank. When household energy consumption exceeds the production from the PV system and cannot be covered by the battery storage, the fuel cell is activated. The household heat demand is met by an air source heat pump, which is also powered directly by the PV system, the battery, or the fuel cell, depending on the production and consumption rates of the system. A hot water tank stores residual heat from electrolysis and the fuel cell, thereby reducing the building heat demand.

The reference systems consist of PV panels, a heat pump, and a battery, but without hydrogen components. It was tested both on-grid and off-grid. While the off-grid system uses a diesel generator as a backup power source, the on-grid system is connected to the public German power grid. Two system comparisons were made: one with the off-grid system, where the SHS is compared to energy supply by a diesel generator, and another with the on-grid system, where extra energy comes from the German power grid. In the on-grid system, electricity is purchased from the grid when the PV system does not produce enough electricity to cover consumption, and the battery is empty. In the case of overproduction, when the electricity and heat demand is met and the battery is fully charged, the surplus electricity is fed into the grid. The SHS requires a larger number of PV panels because it needs to store more energy than the reference system, which has auxiliary energy sources. Results show that the SHS causes lower greenhouse gas emissions in the off-grid scenario. Overall, it is significantly beneficial in 6 out of the 16 assessed environmental impact categories. In contrast, the off-grid reference system, equipped with a diesel generator as a backup power source, presents lower burdens in 7 impact categories and in the single score result. However, when the single score for the HSS is calculated, it shows the highest environmental impact. In the on-grid scenario, the grid-connected reference system is beneficial in all impact categories compared to the HSS. Results heavily depend on the composition of the electricity purchased from the on-grid system. Therefore, this result cannot be generalized for all locations; investigations should be conducted for other countries with different electricity generation structures.

In Peppas et al. [53] the energy supply for a building using renewable sources, such as solar and wind, and the storage of excess energy in the form of hydrogen was also explored Two scenarios were considered: in the first, energy, heating, and cooling are supplied by the electrical grid; in the second, a renewable energy system stores excess energy as hydrogen in a tank at 200 bar, resulting in a 100 % renewable energy supply. In this latter scenario, impacts of construction and maintenance of capital goods were accounted for, aspects not considered in the grid scenario. Data collection for the renewable energy scenario was conducted using a real system. In all analyzed impacts, the renewable energy scenario showed a lower environmental impact, with reductions of 40 %, 42 %, and 35 % in Global Warming Potential, Acidification Potential, and Photochemical Oxidant Formation, respectively, compared to the exclusive use of the Greek electrical grid. The highest impact in this scenario is associated with system construction.

An innovative cogeneration system integrates photovoltaic thermal panels (PV/T), evacuated tube solar collectors, an Organic Rankine Cycle (ORC), and various energy storage methods [54]. Considered that 85–90 % of the solar energy captured by traditional PV panels lost as heat during the conversion process, PV/T offers an efficient solution. The unique aspect of PV/T was the incorporation of heat conduction channels and cooling fluids within the panels, reduced their temperature and captured excess thermal energy. This approach not only lowers the panels temperature, improving electrical efficiency, but also harnesses the generated thermal energy. In this system, water was used as the cooling fluid, and the increase in its temperature within the PV/T can be utilized to provide domestic hot water. The cooling fluid in the PV/T absorbs heat, and it is converted into low-grade thermal energy, that can be used not only for water heating, but also for residual heat recycling. Another option was to use the working fluid of the ORC, which involves an organic substance with a low boiling point. The working fluid absorbs heat from the source in the evaporator, transforming into a high-temperature, high-pressure gas capable of driving the expander to generate power. The ORC was effective in converting low-grade thermal energy into high-quality electrical energy. For energy storage, different technologies were tested, such as batteries and hydrogen production, as well as a combination of these two approaches. The integrated storage system, combining batteries and hydrogen, demonstrated superior performance compared to the use of a single storage technology.

In another work by Rossi et al. [56] the energy supply of a house was provided by a small-scale electrical system that uses PV panels, with excess energy stored in batteries and a hybrid system combining batteries and hydrogen. This energy system operated both on-grid and off-grid. When off-grid, a diesel generator was used to supply energy when the system was not sufficient [56]. Four scenarios were proposed, in which hydrogen is stored and compressed at 350 bar (A) and 700 bar (B). Additionally, future scenarios were considered where excess hydrogen produced at the end of the 25-year system lifespan is treated as a by-product, incorporating extended lifespans at 350 bar (C) and 700 bar (D). Results showed that the system using only batteries was the most sustainable off-grid solution, with a lower environmental impact than scenarios A and B when considered all system impacts, not just CO_{2eq} emissions. This was due to the intensive use of rare materials in fuel cells and hydrogen storage systems. Although the low standby energy consumption of the diesel generator was an environmental benefit, it did not outweigh the disadvantages of hydrogen, unless the lifespan of the fuel cells was significantly extended. In this regard, scenarios C and D were identified as the most promising off-grid solutions. In the final phase of the analysis, off-grid systems were compared to an on-grid solar home system configuration, using nickel-cobalt-aluminum batteries, and avoiding the use of a diesel generator or hydrogen backup. The study concluded that, in the future, connection to a large-scale smart grid will likely represent the most efficient and sustainable configuration.

In another study Florio et al. [41], the LCA was conducted on two different systems for providing energy and heat to a residence, based on on-grid operations. The first system was based on a reversible solid oxide fuel cell and hydrogen storage produced by electrolysis using PV energy, while the second system relied on a solid oxide fuel cell powered by natural gas. The system utilizing PV energy was less favorable from an environmental standpoint, showed a higher impact across all investigated categories. This was primarily because, during periods of low PV energy production, particularly in winter, the increased reliance on the electrical grid further diminishes the environmental performance of the PV system, given the low share of renewable energy sources in Italy's electricity mix. In contrast, the natural gas-powered system had greater energy efficiency, resulting in better environmental performance.

3.4. Power supply to a remote location

Off-grid energy systems are still largely dominated by diesel engines for local electricity generation, despite their environmental drawbacks and high costs associated with fuel transportation. Consequently, there is a significant global potential for integrating renewable energy sources into mini-grids. However, to enhance the utilization of local variable renewable energy sources and improve the reliability of power supply, energy storage solutions must be considered [73]. The use of hydrogen storage for off-grid energy systems has been evaluated in various contexts. Various configurations were evaluated to assess the effectiveness of this approach, including the incorporation of hydrogen storage. Fig. 7 represents the hydrogen storage technologies that were examined in LCA studies focused on power supply for remote locations and the source of energy used to produce hydrogen.

The study by Bionaz et al. [40] compared three energy strategies for a Norwegian island. The REMOTE scenario used PV panels, wind turbines, lithium-ion batteries, and a hydrogen storage system (100 kg tank, 30 bar pressure) with a backup diesel generator. The CABLE scenario supplied electricity via submarine cables from the Norwegian grid, and the DIESEL scenario relied on two local diesel generators. In the REMOTE scenario, renewable generators produced 54.7 % of emissions, while the diesel generator, despite providing only 5 % of energy, contributed 31.8 %. Storage systems had a smaller impact (13.5 %), with batteries slightly outperforming hydrogen. In the CABLE scenario, the submarine cable caused 64.5 % of emissions, followed by Norwegian electricity (25.8 %) and the diesel generator (9.7 %). The DIESEL scenario was the worst, with 80.2 % of emissions from fuel use. Overall, the CABLE scenario had the lowest CO_{2eq} emissions. The worst performance was with the local installation of diesel-fueled generators, because the Norwegian energy matrix is mainly composed of renewable energy.

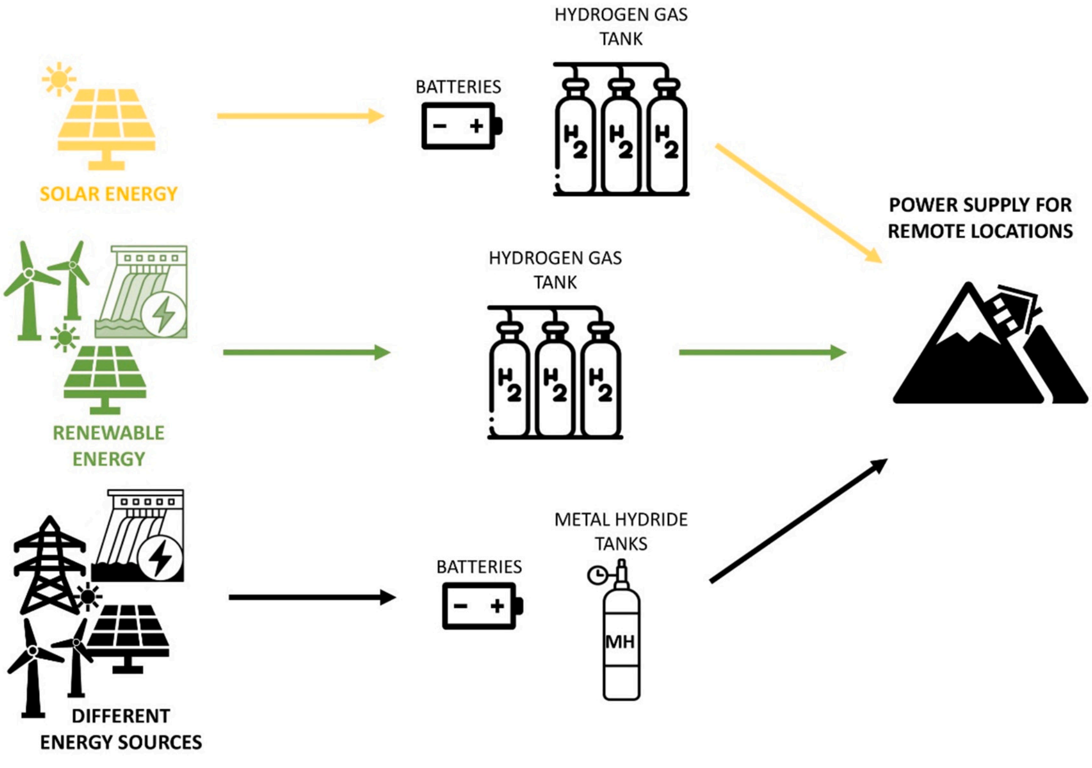

Fig. 7. Diagram illustrating hydrogen storage systems analyzed in LCA studies in the section "Power supply to a remote location", along with the energy sources used for produce hydrogen.

Another study on energy supply for a remote island evaluated CO_{2eq} emissions only for renewable energy supply, from a PV system. As an energy storage system for times when solar energy production is not available, a combination of batteries, an electrolysis system, and a hydrogen tank was studied, considering both storage systems, i.e. hydrogen and batteries [45]. The best environmental performance was observed in the third case, where there is a combination of batteries and hydrogen storage, resulting in the lowest CO_{2eq} emissions. Next is the first scenario, where only batteries were used to store energy generated by PV panels. It is relevant to note that all studied scenarios presented lower carbon emissions than the current diesel-based system.

Gandiglio et al. [43] studied energy provision for remote communities, extending the analysis beyond CO_{2eq} emissions to a broader range of environmental impacts. In the first scenario, energy was generated by a diesel generator, transported by helicopter. The second scenario incorporates renewables with a PV system and a hybrid storage system combining lithium-ion batteries and a hydrogen solution, including an alkaline electrolyzer, fuel cell, and 21.6 m^3 hydrogen tank at 28 bar. A diesel generator remains as backup. Over a 25-year period, the renewable solution improved most environmental categories, except resource use, water use, and freshwater eutrophication. The climate change impact for the scenario using renewables was 0.197 $kgCO_{2eq}/kWh$, compared to 1.73 $kgCO_{2eq}/kWh$ for diesel. The diesel generator still contributed 37 % of climate change impact and up to 70 % of photochemical ozone and eutrophication impacts, with combustion being the largest contributor during operation. Manufacturing was a key factor for other components.

The provision of renewable energy for off-grid facilities, such as astronomical observatories, was examined through a two case studies of an observatory in the Atacama Desert [60,61]. For the first case study, various scenarios were developed to assess the energy supply for the observatory, using diesel generators, PV panels, batteries, and energy storage through hydrogen. Some scenarios involve exclusively renewable energy production, while others combine different sources. None of the energy systems compared emerged as the best in all of environmental impacts assessed. The photovoltaic and battery scenario showed the lowest GHG emissions throughout its entire life cycle, supplying the observatory exclusively with PV energy and battery storage. However, this scenario also had the highest impact on mineral resource depletion. Predominantly renewable systems, with a certain contribution from fossil generation, appear to be the best option in terms of energy reliability, mineral resource depletion, and water usage, although they result in slightly higher GHG emissions compared to 100 % renewable scenarios. The second study conducts an optimization of the system studied in the first case, aiming to optimize environmental and economic performance [61]. Hydrogen-based energy storage proved more cost-effective than lithium iron phosphate batteries, despite requiring a larger PV array due to lower round-trip efficiency, which increased GHG emissions. Battery-based systems had lower GHG impacts, but higher costs due to frequent replacements. Optimized configurations showed up to a 74 % reduction in GHG emissions, with a 12 % cost increase when prioritizing environmental performance.

3.5. *Storage of renewable energy*

To achieve global decarbonization goals, renewable energy sources, like solar and wind, will have to be widely deployed on a large scale worldwide [74]. A key challenge in implementing these renewable energies on a large scale is their unsteady behavior, as they are highly stochastic (e.g. wind) or dependent on daily cycles (e.g. solar). This challenge is currently being addressed through various strategies, with energy storage emerging as a critical solution to support the widespread

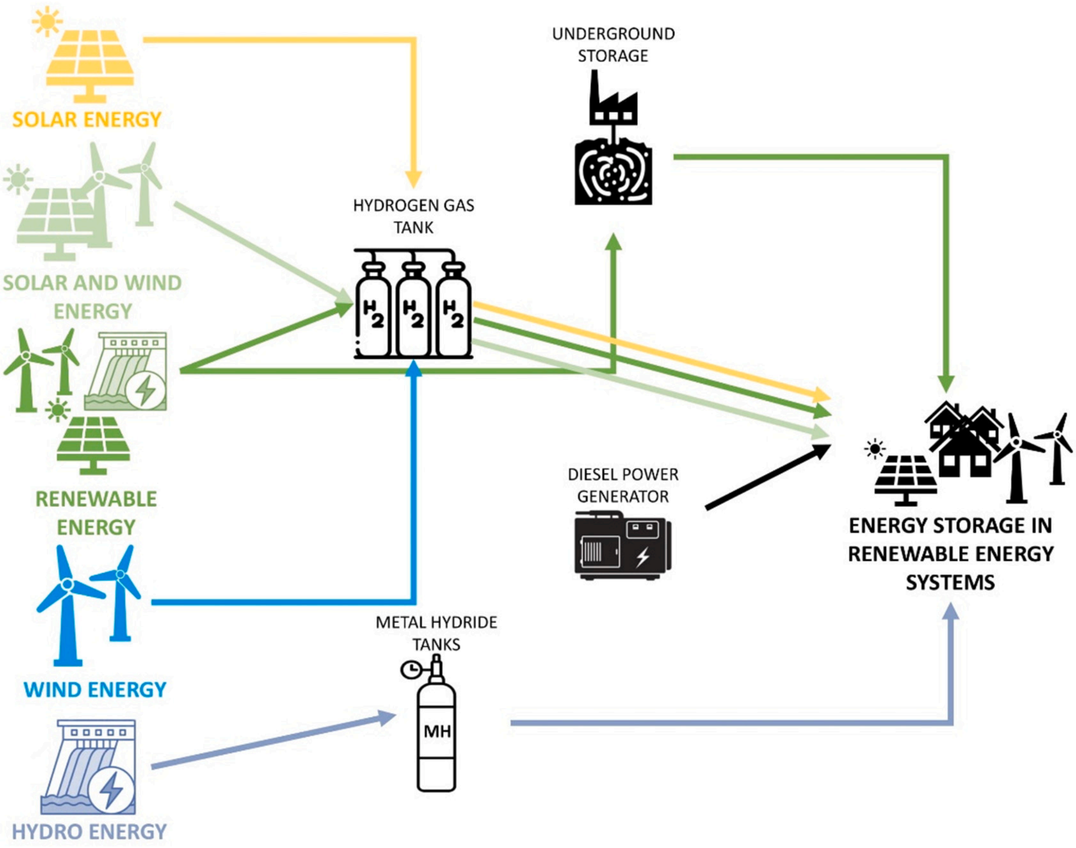

Fig. 8. Diagram illustrating the source of energy used to produce hydrogen and hydrogen storage systems technologies analyzed in LCA studies in the section “Storage of renewable energy”.

integration of renewable energy sources into the energy grid. Therefore, the storage of renewable energy through hydrogen was analyzed across different scenarios and compared with alternative technologies. Fig. 8 depicts the hydrogen storage technologies utilized as energy storage solutions in LCA studies centered on energy production systems.

Autonomous hybrid systems studied by Katsigiannis et al. [47] that used renewable sources as the primary energy supply required supplemental energy from generators or storage technologies, when these sources cannot fully meet the demand. One system evaluated uses batteries for storage alongside wind turbines, photovoltaic panels, diesel, biodiesel generators, and fuel cells. The second employed hydrogen storage in place of the batteries with similar components. The study focused on optimizing the sizing of the components to achieve the best economic and environmental performance. For both systems, the most advantageous configuration included a large number of wind turbines compared to the relatively smaller photovoltaic arrays. The most significant factor influencing economic and environmental performance was the size of diesel generators compared to biodiesel generators. Larger diesel generators result in higher CO_{2eq} emissions, while increasing the size of biodiesel generators tended to reduce these emissions. Furthermore, the use of natural gas-powered fuel cells was not recommended due to their high costs and elevated CO_{2eq} emissions. These findings indicate that the storage system using lead-acid batteries offered the best economic and environmental performance among the alternatives analyzed.

A solar power plant was designed by Fiaschi et al. [42] to generate electricity during the day, storing part of it to meet night-time demand. This study compared different methods of solar energy storage in a power plant with a 20-year lifetime: Compressed Hydrogen Storage (CHS) (350 and 700 bar), Pumped Hydro Storage (PHS), Lithium-Ion Batteries (LIB) and a Thermo-electric Energy Storage System (TEES). The power plant with thermos-electric storage comprises three primary cycles: a supercritical CO_{2eq} power cycle, a heat pump, and a refrigeration cycle, which are indirectly connected through sensible heat storage. The hot reservoir consists of pressurized water maintained at 120–160 °C, while the cold reservoir is a mixture of water and ethylene glycol, kept at −10 to −20 °C. Furthermore, the evaporator section of the power cycle operates on a solar-heated intermediate-temperature heat reservoir, maintained at 95–40 °C. The use of thermal reservoirs makes it possible to compensate for the intermittency of renewable sources, such as solar energy. The results showed that, in continuous operation, the environmental profile of TEES was comparable to that of LIBs and PHS, which had a lower environmental impact, especially LIBs. On the other hand, CHS stands out as the least sustainable storage system, with the 700 bar tank demonstrating the worst environmental performance. This was due to low efficiency and the use of rare materials in the manufacture of electrolyzes and fuel cells, such as platinum group metals.

Valente et al. [59] considered the surplus of energy generated by a hydroelectric plant to produce hydrogen by electrolysis, which was stored in a metal hydride ($LaNi_5$), and subsequently converted into electricity by means of a fuel cell. The analysis of the different parts of the integrated system reveals that environmental impacts were mainly influenced by hydrogen production, especially with regard to global warming potential, and by hydroelectric power generation, with regard to cumulative energy demand. The introduction of hydrogen storage and use in the integrated system results in a moderate increase in life cycle impacts, with the largest contribution coming from the proton exchange membrane subsystem used in power generation. In contrast, the metal hydride storage system exerts a minimal influence, representing about 1 % of the total impact.

The implementation of an energy storage system by Ozbilen et al. [52] for excess energy produced during periods of low demand at a hydroelectric plant and a wind farm aims to avoid the use of thermal power plants during periods of high demand, such as in winter. The system stores excess energy in the form of compressed hydrogen, with an estimated lifespan of 20 years. Results of LCA revealed that the largest contribution to the GWP of the energy storage used hydrogen comes from the fuel cell, followed by the electrolyzer, and finally by the storage itself. The system life cycle resulted in the emission of 31.02 g of CO_{2eq}/kWh of energy supplied when hydrogen storage was utilized. The findings demonstrate that storing excess energy in the form of hydrogen was an environmentally superior solution, compared to the use of fossil fuels during periods of higher energy demand, considering the entire life cycle from production to disposal.

Mostert et al. [49] in order to determine the best solution for energy storage in a renewable energy power plant, eight different renewable energy storage technologies were evaluated, including the storage of methane and gaseous hydrogen, five different battery technologies, and a new underwater compressed air energy storage technology. The second-life battery and the lithium-ion battery present the lowest GWP per electricity supplied [49]. They were followed by underwater compressed air energy storage and hydrogen energy storage. The fact that the energy storage systems with the lowest GHG emissions also showed the lowest material usage indicates a strong correlation between the carbon footprint and the material footprint. For nearly all electrical energy storage technologies, the production phase accounts for the largest share of both material and carbon footprints. However, the analysis reveals that results were sensitive to the proportion of primary versus secondary material and to the energy mix used. Therefore, a higher share of secondary material and the use of energy from renewable sources in the production phase can significantly reduce the impact on climate change and material used for energy storage systems. Results also indicated that the service life and storage capacity had a comparably high influence on the footprints.

Unlike previous studies, a study evaluated different energy carriers for energy storage, including hydrogen, ammonia, and methane, as well as two reference systems: one representing a future scenario in which natural gas was utilized but produced from CO_{2eq} generated during combustion, and another reflected current technology, based on energy generation through the combustion of natural gas [32]. The analysis of two natural gas combustion reference systems showed that carbon capture and storage can reduce direct CO_{2eq} emissions by about 70 %, significantly lowering climate change impacts over the life cycle. However, this reduction increases impacts in other environmental categories. In contrast, systems used hydrogen, ammonia, and methane showed substantial reductions in three out of seven impact categories: an 80 % reduction in climate change impact, 40–50 % in photochemical ozone formation, and 90 % in fossil resource scarcity. Nonetheless, these new energy carriers lead to greater impacts on particulate matter, marine eutrophication, and mineral resource scarcity compared to natural gas systems. The natural gas reference system had the lowest terrestrial acidification impact, while the ammonia system has the highest. In comparison hydrogen, ammonia, and methane: the LCA showed that the use of hydrogen for storage has the lowest environmental impact across all categories. The main sources of environmental impact for the reference system were natural gas extraction and transport, while significant impacts for renewable processes come from producing and installing PV and wind capacity.

Several studies have explored energy storage solutions for integrating energy storage systems with electrical grids. To facilitate the incorporation of new renewable energy sources into Brazil's electrical grid, two distinct technologies have been evaluated for the storage of excess energy [37]. The first alternative involves the use of the surplus energy to pump water from a downstream reservoir of a hydroelectric plant to an upstream reservoir. The second considered using excess energy to produce hydrogen through water electrolysis, storing it at a pressure of 10.3 MPa. Both alternatives include the subsequent generation of energy when needed for end use. The only environmental impact assessed was CO_{2eq} emissions. Pumped hydro storage (PHS) offers distinct advantages over hydrogen storage in two critical areas: efficiency and environmental impact. PHS proves its sustainability by requiring only 84 % of the total exergy cost and emitting just 23 % of the CO_{2eq} compared to the hydrogen storage option.

Oliveira et al. [51] evaluated different energy storage systems, considered essential for backup and balancing in large-scale power grids, including compressed air and pumped hydro storage as mechanical storage methods, as well as advanced batteries and hydrogen production via electrolysis. The results show that the environmental performance of these systems is highly influenced by the source of the electricity used. Choosing the right storage system was crucial, as its impact can be minimal without proper application. High-efficiency storage units offer significant climate change mitigation opportunities. Technologies with the lowest CO_{2eq} emissions include lithium-ion, nickel-sodium chloride, and sodium-sulfur batteries. For human toxicity, low impacts were noted in large-volume, moderate-efficiency systems like pumped hydro and compressed air energy storage. To minimize particulate matter emissions, storage energy produced by wind farm is the most effective, as other combinations, including photovoltaics, exceed Belgium's 2011 emissions average. Few technologies significantly mitigate fossil fuel depletion, with the best being those that didn't increase infrastructure impacts when powered by renewables. A 100 % wind energy mix showed the greatest reduction potential in large-volume, moderate-to-high efficiency storage systems. Overall, rechargeable energy storage systems presented a viable alternative to thermal resources. Hydrogen storage and subsequent consumption in fuel cells had the worst environmental score, while pumped hydro, compressed air energy storage, sodium-sulfur batteries, and nickel-sodium chloride batteries systems performed better, especially with wind energy.

Jiao and Månsson [46] conducted a LCA of the transition of the Swiss energy matrix to a 100 % renewable configuration, replacing fossil sources with wind and solar energy. Due to the intermittency of these sources, different combinations of renewable energy storage systems were evaluated, including pumped hydro storage, hydrogen storage, lithium-ion batteries, lead-acid batteries, vanadium redox batteries, supercapacitors, and flywheels. In all the scenarios studied, two approaches were analyzed. In the first, renewable energy was generated, and a biomass-based backup system was activated whenever generation was insufficient to meet demand. In the second approach, extra renewable energy production was implemented and stored for later use. Different combinations of storage technologies were tested. The results indicate that GHG emissions from energy storage systems have a significant impact on total life cycle emissions due to underutilization over time. Among the systems analyzed, the combination of pumped hydro storage, lithium-ion batteries, and flywheels exhibited the lowest emissions. Additionally, Hybrid Energy Storage Systems (HESS) effectively reduced GHG emissions compared to systems that rely on biomass as a backup energy source.

4. CO_2 emissions

Among selected studies that performed an LCA of hydrogen storage systems, a comparison of CO_{2eq} emissions per kWh of the energy system, was present in detail in Section 3, was conducted. Some studies were excluded from the analysis due to the absence of kg CO_{2eq}/kWh values or insufficient data for unit conversion. To ensure a meaningful comparison, the system boundary had to encompass hydrogen production, storage, and consumption. The results selected for this comparison represent the hydrogen storage systems with the lowest emissions from each study for each storage technology analyzed. For example, if a study evaluated multiple hydrogen production technologies, the system with the lowest emissions was chosen. However, if more than one storage technology was analyzed, both will be presented. For studies reporting emissions in CO_{2eq}/kgH_2, the values were converted using the calorific value of hydrogen, where 1 kg of hydrogen corresponds to 33 kWh of electricity. Results of the comparison are presented in Figs. 9, 10, 11 and 12.

In Fig. 9, it is possible to observe the influence of hydrogen storage technology on kg CO_{2eq}/kWh emissions. The lowest emissions are associated with metal hydride and underground hydrogen storage. In contrast, compressed gas storage in tanks shows a wide range of CO_{2eq} emissions. Hydrogen storage combined with batteries performs well in the comparisons made within this study, but it exhibits higher emissions than metal hydride and underground hydrogen storage. When assessing the impact of the energy source on the storage system (Fig. 10), consistent with findings from various studies [39,41,44,47,57,58], it is evident that the energy source used for hydrogen production plays a key role in determining the system's overall emissions. Wind and hydroelectric power emerge as the most sustainable options, resulting in the lowest CO_{2eq} emissions.

Based on the classification of applications presented in this study (Fig. 11), the highest specific CO_{2eq} emissions were observed in the *Energy storage for terrestrial transport* category, followed by *Power supply to a building*, *Power for remote location*, and finally *Storage of renewable energy*. This distribution suggests an inverse correlation between emissions and the scale of the storage systems, indicating that larger-scale applications tend to exhibit lower environmental impacts per functional unit. The lowest emissions were identified in the *Hydrogen storage assessment* category, which includes systems without a clearly defined end-use application or those that do not fit into the other established categories.

Fig. 12 illustrates the relationship between CO_{2eq} emissions and the capacity of the considered hydrogen storage system. As the container

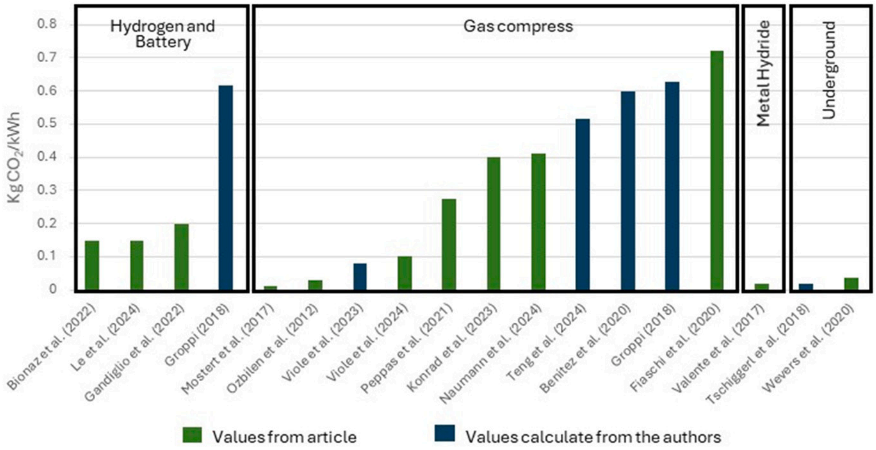

Fig. 9. kg CO_2 emissions per kWh of energy produced by the examined integrated systems (that include energy source, H_2 production and storage and fuel cell) using different hydrogen storage technologies.

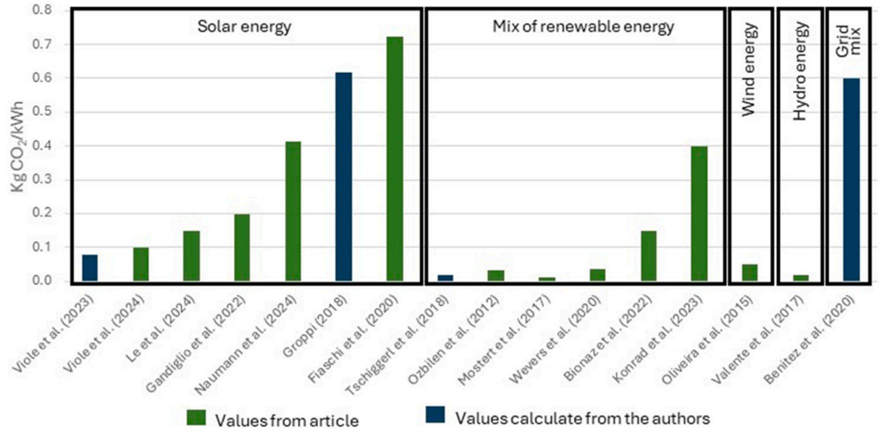

Fig. 10. kg CO₂ emissions per kWh of energy produced by the examined integrated systems (that include energy source, H_2 production and storage and fuel cell) using different energy sources for H_2 production.

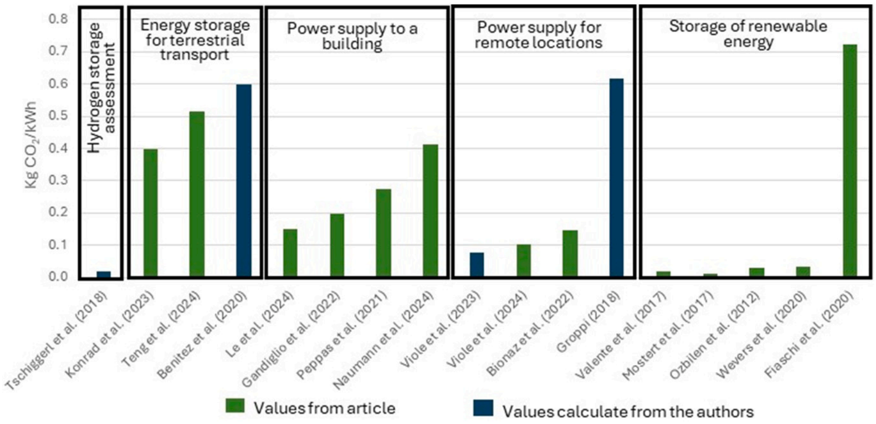

Fig. 11. kg CO₂ emissions per kWh of energy produced by the examined integrated systems (that include energy source, H_2 production and storage and fuel cell) using different hydrogen storage for application.

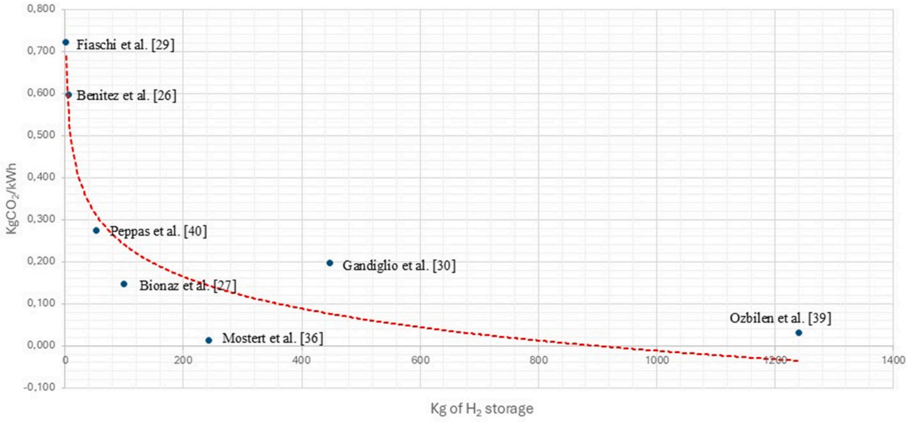

Fig. 12. CO₂ emissions per kg of hydrogen storage capacity. The red line represents a fit highlighting the trend of the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

capacity increases, CO_{2eq} emissions decrease. A line highlights this trend, showing a clear reduction in emissions with larger hydrogen storage volumes. This effect is likely attributed to the optimized design of the integrated storage systems at a large scale, that allows the optimization of the amount of materials used for the production of the system, usually not possible when small systems or prototypes are involved. As in many articles the environmental impacts are related to the production of the integrated storage system, its optimization can reduced consumption of certain components at a larger scale, leading to lower overall emissions.

5. Integrating environmental, economic and social sustainability

The development of a new hydrogen-based energy matrix, in order to be truly sustainable, must go beyond addressing environmental challenges and adopt a more comprehensive approach. Sustainability requires balancing economic growth, social progress, and the responsible use of natural resources, ensuring both ecosystem preservation and the well-being of present and future generations.

In a life cycle study, social and economic aspects can be integrated with environmental aspects in a framework known as Life Cycle Sustainability Assessment comprising LCSA = LCA + LCC + SLCA [75]. LCSA extends the scope of the decision-making process by integrating social and economic aspects, as an effective tool encompassing the environmental, social, and economic impacts in life cycle perspective [76]. Despite the growing interest in LCSA, significant challenges and gaps remain in the integration of its three pillars. The level of methodological maturity shows significant differences among the pillars. While the environmental assessment is generally well-established, the evaluation of social and economic impacts lacks harmonisation and standardisation, resulting in heterogeneous outcomes and interpretations [77]. However, recent initiatives have been proposed with the aim of integrating the social dimension more comprehensively into the assessment of hydrogen-related energy systems. For instance, the European initiative [78] is focused on the development of LCSA guidelines for hydrogen-related systems.

Although the literature on this subject is limited, there are some relevant studies that integrate economic and social aspects into a life cycle sustainability assessment of hydrogen production [24,79–81] or hydrogen-related technologies [82–84]. This current body of research establishes the basis for the future development of suitable practices that will enable the integration of the social dimension into the life cycle framework of hydrogen-related products. Further progression in the direction of establishing a more comprehensive and thorough framework would necessitate the advancement of studies on the Life Cycle of Hydrogen-related systems (S-LCA).

6. Conclusions

When analyzing different LCAs of energy storage systems using hydrogen as an energy carrier for various purposes, some common observations emerged. In hydrogen-based energy storage systems, when hydrogen is produced using renewable energy, most of the environmental impacts are associated with the system's construction [42,49,53]. Therefore, extending the system's lifespan contributes to a reduction in total impacts [56]. The electrolyze and fuel cell are identified as the primary sources of environmental impact in these systems [42,52,59].

The combination of multiple storage technologies proves to be advantageous, as it distributes environmental impacts across different categories, given that each technology tends to perform worse in specific impact indicators [31,45,54]. Moreover, using various energy sources for hydrogen production can offer additional benefits [31,56]. However, when comparing this study with other results, metal hydrides and underground storage exhibit lower CO_{2eq} emissions. Nevertheless, the number of LCA studies on these two technologies is limited, highlighting the need for further research. Another important observation is that increasing the scale of the storage system leads to a reduction in CO_{2eq} emissions.

The results obtained in this work show that a wide range of applications and scales are being evaluated through Life Cycle Assessment (LCA), which reflects a growing awareness among hydrogen storage technology developers of the importance of LCA in developing a low-environmental-impact hydrogen supply chain. However, most studies still focus on hydrogen storage in the form of compressed gas and on assessing the GWP of the technologies. There is a clear need to deepen the investigation of alternative storage methods and to broaden the analysis to include other environmental impact categories. Thus, it is recommended that future studies consider a wider range of emerging technologies, with more robust analyses that are not limited solely to CO_{2eq} emissions. Environmental impacts such as human toxicity, land use, water consumption, and natural resource depletion should be incorporated into these assessments.

Several technologies analyzed as alternatives to compressed gas demonstrated good environmental performance, indicating that they may represent promising solutions for hydrogen storage. Moreover, new studies should adopt more comprehensive approaches, integrating environmental sustainability with economic and social dimensions. This integration is essential, given that sustainable development requires balancing economic growth, social progress, and the responsible use of natural resources, thereby ensuring both ecological balance and the well-being of present and future generations. Multidimensional assessments are therefore fundamental to supporting more consistent decisions aligned with the principles of sustainability.

Joint analysis of environmental and economic aspects is already present in one third of the studies evaluated in this work. However, only one study explicitly considered social impacts, revealing a clear opportunity to expand the scope of assessments through the adoption of more integrated methodologies.

A particularly relevant tool for complementing Life Cycle Assessment in multidimensional studies is Multi-Criteria Decision Analysis (MCDA). This approach helps decision-makers make more informed choices in complex contexts, such as those involving LCA, where multiple factors and impacts must be considered simultaneously. MCDA is a mathematical methodology that integrates the values and preferences of decision-makers and stakeholders with technical information in order to select the best solution or provide a ranking of alternatives for a given problem [85]. Thus, we can achieve a LCA approach that ensures a comprehensive evaluation and supports decision-making aimed at developing a new energy matrix with lower environmental impact, reduced costs, and a positive social impact for society.

CRediT authorship contribution statement

Ediane Alves: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Jacopo Bindi:** Writing – review & editing. **Francesca Garelli:** Visualization. **Claudio Carbone:** Writing – review & editing, Project administration, Conceptualization. **Alessandro Agostini:** Writing – review & editing, Project administration, Conceptualization. **Giuseppe Pellegrini-Masini:** Writing – review & editing. **Dario Padovan:** Writing – review & editing. **Marcello Baricco:** Writing – review & editing. **Paola Rizzi:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no competing interest to declare.

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Data availability

Data will be made available on request.

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