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The role of hydrogen in mining decarbonisation

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A B S T R A C T

The mining sector faces increasing pressure to decarbonise. Hydrogen is emerging as a versatile energy carrier for high-demand applications such as heavy-haul trucks, excavators, and ore processing. This review synthesizes developments in hydrogen production, storage, transportation, vehicle deployment, safety, and modelling, drawing on over 170 studies and industrial projects published in the last decade. Pilot projects already demonstrate hydrogen-powered mining trucks and excavators, achieving 60–95 % emission reductions compared to diesel. Hydrogen is also being trialed in industrial processes, including iron ore reduction, hydrogen-powered calcination, and direct steel reduction. Projected demand for large mines is 5–10 t H_2/day, with near-term levelised costs estimated at 3–6 USD/kg. Compared with battery-electric systems, hydrogen offers a longer driving range, higher energy density, and rapid refueling. It can be especially advantageous in remote sites where reliable power supply and charging infrastructure are limited, though challenges remain in cost, infrastructure, and safety. Beyond technical aspects, successful deployment requires robust supply chains, regulatory frameworks, and safety standards. Looking ahead, hydrogen integration may expand to on-site electrolysis and sector coupling with renewable fuel production, enabling flexible low-carbon energy systems. By identifying realistic opportunities and hurdles, this review outlines pathways for hydrogen adoption in mining and supports the sector's transition to sustainable, low-carbon raw material production.

1. Introduction

Mining is one of the most energy-intensive industries, responsible for 4–7 % of global emissions [1]. With global population growth and the rise of many low-income economies to middle-income countries, demand for raw materials will continue to increase. Combined with declining ore grades, this trend is expected to further raise the sector's energy needs [2]. Mines operate under diverse energy system configurations, ranging from grid-connected to off-grid setups, each differing in size and energy demand. Historically, fossil fuels like coal, diesel, and natural gas have been the backbone of mining operations. Diesel machinery, for instance, is widely used in mining for its mobility and ability to operate in remote areas lacking electrical infrastructure [3]. However, the reliance on fossil fuels, especially in energy-intensive activities such as the loading and transportation of ore, poses significant challenges: high greenhouse gas emissions, vulnerability to fluctuating fuel prices, and supply chain risks associated with the geographic concentration of fossil fuel resources [4]. These factors are intensifying the pressure on the mining sector to decarbonise.

The world is already exploring the possibilities of decarbonising mines. In this context, socio-environmental-economic feasibility studies [1], life cycle assessments [5,6] and techno-economic assessments [7–9] are being conducted. The mining industry is looking for new technologies to comply with environmental regulations [10]. New technologies in mining are transforming industry by enhancing efficiency, safety, and environmental sustainability. Innovations such as automation, digitization, and advanced extraction methods are being implemented to improve operational performance [11–13]. There are also ongoing initiatives such as the European project Digital and innovative mine of the future (DINAMINE), which aims to transform the mining value chain through digitalization and innovation. It is piloting a data-driven mine management system using AI and sensors for real-time monitoring of performance, risks, environmental impact, and recovery rates. Technologies are being demonstrated in two operational mines, covering the

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mine-to-port chain. The project advances machinery automation, selective mining, and ore sorting to improve efficiency and reduce waste. It also explores best practices for carbon-neutral logistics, energy-efficient processing and sustainable waste management [14].

The mining sector has the potential to utilize various clean energy solutions, including energy efficiency, energy recovery, renewable energy and carbon capture technologies [2,15]. A combination of these clean energy technologies is required to fully address the energy challenges in mining. Studies emphasize the role of renewable electricity, particularly solar, wind, geothermal, and energy storage as cost-effective options for mines. Beyond emissions reduction, renewable integration offers mining companies the chance to improve operating margins, hedge against fossil fuel price volatility, stimulate local economic development, and strengthen their social license to operate. However, despite this momentum, technical and operational challenges persist: mining's continuous, energy-intensive loads cannot always be met by variable renewables alone, making hybrid systems and careful planning essential for successful decarbonisation [2,9]. Electrification of equipment and processes, from haul trucks to mineral processing, is increasingly seen as a pathway to reduce dependency on fossil fuels. In particular, transitioning heavy-duty vehicles and stationary machinery to electric power, when supplied by renewable electricity, can significantly cut greenhouse gas emissions and improve energy efficiency. Electrification also reduces exposure to fuel price volatility and improves local air quality, while in combination with renewables it enables deeper decarbonisation across the mining value chain. Nevertheless, challenges remain in providing sufficient charging infrastructure and ensuring reliable supply for continuous, energy-intensive mining operations [16].

While electrification offers substantial opportunities, it is not always feasible for all mining applications, particularly for large haulage and energy-intensive processes. In this context, hydrogen has emerged as a versatile and potentially transformative energy carrier, providing an additional pathway to reduce dependency on fossil fuels. Various activities in the mining sector could benefit from hydrogen, including generating high-temperature heat, power, feedstock, energy storage, and fuel for transportation [17,18]. Hydrogen is a clean energy carrier that presents both opportunities and challenges for the mining industry. It can be produced using a variety of methods, including electrolysis powered by renewable energy sources and used in fuel cells to power mining equipment and vehicles, reducing greenhouse gas emissions and improving air quality in mines [10]. Hydrogen offers also the ability to decouple energy production from specific geographic regions [19]. Its versatility makes it suitable for powering both stationary operations and mobile equipment with long range, compared to battery vehicles [20]. In addition, hydrogen has several other advantages over batteries in mining operations [10,21]: Hydrogen refueling takes only minutes, whereas battery charging can require several hours, potentially impacting shift scheduling and operational efficiency [22]; Hydrogen has a higher energy density, allowing heavy-duty machinery to operate without excessively large or heavy power storage, while batteries may limit machine range or require oversized battery packs [23,24]; Hydrogen fuel tanks are lighter and more compact than equivalent battery systems, improving mobility in challenging terrains [25]; Hydrogen fuel cells experience less degradation over time, maintaining stable performance for longer periods compared to batteries, which lose capacity over repeated charge cycles [26]. Despite these benefits, the introduction of hydrogen in mining is not without its challenges. It requires significant changes in infrastructure and logistics, as well as investment in new technologies and personnel training [2]. Overall, hydrogen and battery-electric technologies offer complementary solutions rather than mutually exclusive options, and the optimal choice depends on the specific mining application, operational scale, and energy requirements.

This review article examines the status of hydrogen use in mining and demonstrates its potential to transform the sector into a more sustainable and environmentally friendly industry. Table 1 summarizes how this review differs from previous contributions.

Our article stands out in two main respects. Firstly, it is entirely dedicated to hydrogen in the context of mining, whereas many existing reviews address hydrogen only marginally within broader discussions of renewable energy. Secondly, within mining focus, we provide a comprehensive perspective, while previous works typically consider only a single hydrogen-related aspect. Importantly, our contribution is grounded in practical applicability: for mining stakeholders, it is essential to be familiar with the various methods of hydrogen production, transportation, and storage (Section 3). As well as to be informed about ongoing mining projects involving hydrogen, it is beneficial from an overview of hydrogen-powered mining vehicles, which provides an immediate reference for identifying the most suitable options. The inclusion of vehicles from the transport sector highlights alternative solutions relevant to mining operations (Section 4). In addition, the article covers economic aspects (Section 5), safety considerations (Section 6), and modelling approaches for assessing hydrogen's potential to transform energy use in mining (Section 7). The article concludes with the future role of hydrogen in mining.

2. Reviewing methodology

To provide a comprehensive and up-to-date review of hydrogen adoption in mining, we employed a structured and multi-source methodology combining systematic academic literature searches with targeted reviews of industrial and public-domain materials.

The academic literature review was based on searches in databases Google Scholar, ScienceDirect, and AI/SciSpace using combinations of keywords. The main terms were mining, mine, hydrogen, while additional keywords varied by section (Section 1): – decarbonisation, sustainability, sector, industry, green, vehicles, renewable energy, electrification, battery, electric, replacing fossil fuels, machinery, innovative, fuel cell, strategy, carbon-neutral (Section 3); – production, transportation, storage, colors of hydrogen, fuel cell (Section 4); – truck, heavy-duty vehicle, excavator, long-haul truck, equipment, off-road vehicle, projects, economic feasibility (Section 5); – safety, hazards, past incidents, mitigating, risks, detector, fire, ventilation, emergency, regulations, standards (Section 6); – modelling, hybrid systems, techno-economic assessments, techno-economic analysis, numerical study, energy systems. Search strings were iteratively refined to capture studies across the domains of hydrogen technology and mining industry. Publications were limited to English-language peer-reviewed articles, conference proceedings, and selected book chapters published mainly in the previous decade, with seminal earlier works included when conceptually relevant. Initially, approximately 250 publications were identified through broad keyword searches. From this pool, more specific searches were then conducted for each thematic section to refine the dataset and ensure sufficient depth of coverage. Screening followed a three-step process: (i) identification of records, based on which the thematic sections were defined, (ii) exclusion of thematically irrelevant items, and (iii) inclusion of studies addressing specific topics related to hydrogen and mining.

To complement academic insights with sectoral practice, we systematically consulted industrial reports, e.g. Hydrogen Council and IEA Global Hydrogen Review, company announcements, mining sector newsletters, and specialized trade magazines. Targeted Google searches combining technical keywords with company names were used to trace ongoing industrial initiatives and pilot projects. In addition, Mission Hydrogen Webinar Series was considered to capture emerging practices. Furthermore, reflections and practical insights from miners engaged in the DINAMINE project were integrated, ensuring that the review remained grounded in operational realities and sector-specific challenges.

Table 1
Comparative analysis of the current review vs. previous studies associated with hydrogen-based mining decarbonisation.

Previous article			Present article
Year/Author/ Ref.	Title	Focus	
2020 Romero et al. [27]	100 % renewable fueled mine	Feasibility and cost-effectiveness of supplying a remote underground mine with wind power and hydrogen storage.	A comprehensive hydrogen utilization and potential for all types of mining.
2020 Sam-Aggrey [28]	Assessment of the impacts of new mining technologies: recommendations on the way forward	Implications of automation, digitalization, and battery electrification, for environmental, socio-economic aspects and regulation of mines.	Technological and application-oriented perspective to enable mining decarbonisation.
2021 Igogo et al. [29]	Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches	Solar, wind, geothermal, storage, hydrogen – integration into mining to reduce costs, emissions, and fossil fuel dependence.	Focus on detailed hydrogen-centred use in mining.
2021 Nurdiawati et al. [30]	Towards deep decarbonisation of energy-intensive industries: A review of current status, technologies and policies	Decarbonisation of steel, mining, cement, pulp and paper, refineries industries in Sweden via electrification, low-carbon fuels, hydrogen, carbon capture and storage, and efficiency.	Focus on mining industry and hydrogen technology.
2022 Camacho et al. [31]	Hydrogen fuel cell heavy-duty trucks: Review of main research topics	Hydrogen fuel cell transport-oriented article, mainly addressing on-road trucks, with technological, policy, and supply chain aspects as a decarbonisation pathway.	Includes off-road trucks and other mining-specific vehicles. In addition, it explores hydrogen use more broadly across mining operations.
2022 Pardhi et al. [32]	A review of fuel cell powertrains for long-haul heavy-duty vehicles: Technology, hydrogen, energy and thermal	Fuel cell technologies for long-haul heavy-duty road transport. Additionally, hydrogen production, storage, refueling, energy and thermal management, and performance analysis.	Hydrogen heavy-duty off-road vehicles for mining operations. Additionally, economical, safety and modelling aspects.
2022 Sakinala et al. [33]	A review of conventions, protocols, and agreements: Importance of sustainable mining in achieving sustainable development goals	Conventions, protocols and agreements on sustainability, together with sustainable development goals in general, and with consideration of the context of mining.	Focus on hydrogen technology aspects for mining as a contribution to achieving sustainability.
2023 Figueiredo et al. [34]	Green hydrogen: Decarbonisation in mining - Review	Green hydrogen for replacing diesel in mining, covering production methods, technical applications, challenges and its potential to reduce emissions.	Includes concrete examples of implementing hydrogen in mining, along with its safety considerations and modelling aspects.
2023 Peppas et al. [35]	Environmental assessment of replacing fossil fuels with hydrogen for motorised equipment in the mining sector	Life cycle assessment to evaluate emissions and environmental performance when using hydrogen for mining equipment.	A broader technology- and application-oriented perspective across multiple mining processes, infrastructure, safety, regulatory aspects, and modelling.
2023 Pouresmaieli et al. [16]	Integration of renewable energy and sustainable development with strategic planning in the mining industry	The current energy situation in the mining industry and the potential for integrating renewable energy to achieve sustainable development through strategic planning.	More specific and technical, focusing on hydrogen for mining decarbonisation.
2024 Kurc et al. [36]	Hydrogen-powered vehicles: a paradigm shift in sustainable transportation	Hydrogen production and storage, emphasizing hydrogen vehicles (personal transport) compared to battery electric vehicles.	Hydrogen mining vehicles and hydrogen related projects in mining. Additionally, economical, safety and modelling aspects.
2025 Amegboleza et al. [37]	Sustainable energy transition for the mining industry: A bibliometric analysis of trends and emerging research pathways	Energy transition in mining, covering trends, research pathways, renewable energy integration – solar, wind, hydrogen, and economic, regulatory, and policy aspects.	Focus specifically on hydrogen integration, providing concrete examples of vehicles, process options, with related infrastructure, economic, regulatory, and modelling aspects.
2025 Present article	The role of hydrogen in mining decarbonisation	Hydrogen supply, use in mining processes and heavy-duty vehicles, hydrogen economic, safety and modelling for mining.	Unique contributions: consolidates hydrogen applications in mining, providing practical, sector-relevant examples across vehicles, processes, infrastructure, economy, safety,

(continued on next page)

Table 1 (*continued*)

Previous article			Present article
Year/Author/ Ref.	Title	Focus	
			regulation, and modelling.

3. Hydrogen production, transportation and storage

Hydrogen is a low-emission and versatile energy carrier alternative in the fossil fuel-dominant mining industry. This section introduces key technologies for hydrogen production, transportation and storage. Technologies can be broadly divided into two categories based on the logistics needed for the availability of hydrogen at a mining site and/or processing plant, i.e. on-site and off-site.

a) *On-site:* Mines with sufficient energy resources can produce hydrogen on-site, simplifying logistics but requiring significant investment and carrying higher risk. Green hydrogen, produced using electrolyzers, is the most practical option in such cases [38].
b) *Off-site:* For mines unable to produce hydrogen on-site, supply can be sourced from local or distant facilities. Local production could leverage abundant renewable energy, favorable regulations and shared production within a local ecosystem, while allowing hydrogen to be transported in compressed gaseous form to nearby mines with minimal on-site infrastructure. Distant production facilities would benefit from economies of scale, with large scale facilities in low-cost energy regions, though long distances would require energy-dense intermediaries for transport, requiring specialized conversion and conditioning infrastructure at both ends [39].

These categories highlight the versatility of hydrogen as a fuel and provide a framework for evaluating its adoption in mining operations. Fig. 1 shows the different options for hydrogen production, transportation and storage for mining operations.

One can find several recent reports on the global status of the hydrogen value chains, e.g. The Global Hydrogen Review by the International Energy Agency [40] or the Global Hydrogen Compass by the Hydrogen Council and McKinsey [41]. The uptake of low-emission and renewable hydrogen is not fulfilling the ambitions sets in the past years, mostly due to cost and uncertainty in demand and regulation, although one could expect a strong expansion from 2030 [40]. Despite of the amount of announced hydrogen projects (from 305 billion $ in 2024 to 285 in 2025) there are still 300 billion $ of projects planned (Feasibility and Front End Engineering and Design studies), and the amount of committed projects (Final Investment Decision, under construction and operational) in production, distribution/infrastructure and end use of hydrogen has increased from 75 billion $ in 2024 to 110 in 2025 [41]. The following subsections of the value chain will include the overall status of commercial and pilot scale plants.

3.1. Hydrogen production

Hydrogen production is often classified by color codes [42] reflecting the energy source and production method. Each color represents the environmental impact and sustainability of the production pathway, as summarized in Table 2. Currently, the majority of hydrogen is produced from fossil fuels, resulting in significant CO_2 emissions [43]. This production is primarily through natural gas reforming, lignite coal gasification, or bituminous coal gasification, leading to grey, brown and black hydrogen, respectively. On the other side of the environmental spectrum, green hydrogen is produced via water electrolysis powered by renewable energy sources such as wind, solar, or hydroelectric power, making it an environmentally friendly and sustainable option. In between, blue hydrogen is generated from natural gas combined with carbon capture, utilization, and storage technologies, which capture and store the CO_2 emissions. Turquoise hydrogen is produced through methane pyrolysis, a process that yields solid carbon instead of CO_2, making it a low-emission alternative [44]. Other colors include yellow hydrogen, which is produced using grid electricity, pink hydrogen, which uses nuclear energy to power the electrolysis process, and purple hydrogen, which is also derived from nuclear energy but produced through thermochemical processes using high-temperature heat from nuclear reactors. White hydrogen, naturally occurring in the Earth's crust, offers a potential clean energy source, though its extraction remains challenging [45].

For new hydrogen producers aiming to reduce CO_2 emissions, focusing exclusively on low-emission hydrogen is essential [46]. Electrolyzers are a key technology in the production of low-emission hydrogen, particularly green, yellow, and pink hydrogen, where water is split into hydrogen and oxygen using electrical energy. The primary types of electrolyzers include alkaline electrolyzers, which use liquid electrolytes and are suitable for large-scale systems but face difficulties in adapting to variable renewable energy sources [47]; proton exchange membrane (PEM) electrolyzers, which use solid polymer electrolytes, offering compact, responsive systems but with higher costs and demanding water purity [48]; and solid oxide electrolysis cells (SOEC), which operate at high temperatures and benefit from industrial heat, offering high efficiency, but facing challenges related to material

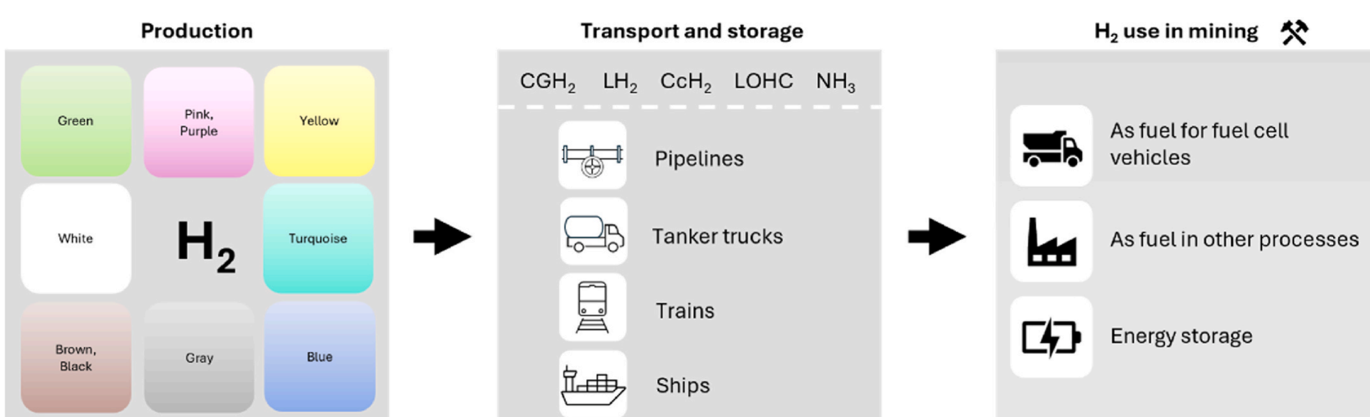

Fig. 1. Scheme of the hydrogen (H_2) supply chain relevant to mining operations. Hydrogen can be produced via various pathways, illustrated as different "colors" of hydrogen, and transported or stored using pipelines, trains, tanker trucks, or ships. Multiple hydrogen carriers and storage forms are included: compressed gaseous hydrogen (CGH_2), liquid hydrogen (LH_2), cryo-compressed hydrogen (CcH_2), liquid organic hydrogen carriers (LOHC), and ammonia (NH_3). Hydrogen is ultimately used in mining applications. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Overview of hydrogen production methods.

Hydrogen "Color"	Energy Source	Production Method	Carbon Emissions	Key Features	Challenges
Green	Solar, wind, hydro power	Water electrolysis	None	Zero emissions, off-grid option	Cost depends on renewable input, intermittent production
Pink / Purple	Nuclear power	Water electrolysis	Very low	Stable base-load – not weather dependent	Public perception, nuclear waste management
Yellow	Electricity from the grid	Water electrolysis	Varies with grid	Uses existing electricity infrastructure	Emissions depend on grid
Turquoise	Natural gas	Methane pyrolysis	Low	Avoids CO_2 release (produces solid carbon)	Technology still emerging
Blue	Natural gas	Natural gas processing and carbon capture & storage	Medium	Mostly uses existing infrastructure	Carbon capture and storage add cost
Grey	Natural gas	Natural gas processing	High	Mature technology	CO_2 intensive
Brown / Black	Coal	Gasification	Very high	High H_2 output	High GHG emissions
White	Natural – geology sources	No production needed	None	Naturally occurring	Rare

stability and durability [49]. These technologies play a crucial role in advancing the transition toward low-carbon hydrogen production, particularly as renewable energy sources continue to scale globally.

Emerging electrolyzer technologies like anion exchange membrane (AEM) cells are still in development and not yet ready for industrial-scale deployment [50], while thermochemical water splitting, a novel approach, uses high temperatures to drive intermediate reactions that ultimately split water into hydrogen and oxygen [51–53]. This method, which could become more favorable than photovoltaic-powered electrolysis, requires further research to scale up from lab to industrial use [54], with heat supplied by low-carbon sources like concentrated solar [51] or nuclear energy [55,56]. Additionally, biomass gasification is being explored as a hydrogen production pathway [57,58], though large-scale implementation would consume a significant portion of limited biomass resources.

Focusing on the clean hydrogen operational production capacity, it is dominated by low-carbon technologies (mostly blue, but this category can also include turquoise, pink and yellow hydrogen), led by North America and with a capacity 690 ktpa. Renewable hydrogen (green hydrogen) is dominated by China and has a total operational capacity of 315 ktpa in 2025, which has increased by 65 % since the last year and multiplied by 8 in the last five years [40]. The main technologies are blue and green hydrogen, with biomass-to-hydrogen and methane-pyrolysis playing a more marginal role [41]. China leads the electrolyser market and has the lowest electrolyser costs, but for other parts of the world, when transport costs and tariffs are included, the gap with other producers is reduced [40].

The largest electrolysis plant by the latest reports is the Xinjiang Kuqa Green Hydrogen Pilot Project (260 MW or 20 ktpa H_2), and it includes storage tanks for 270 000 Nm^3 and a transmission pipeline to the Tahe Refining and Chemical (28 000 Nm^3/h installed capacity) [40]. Other relevant production plants with other hydrogen-derived energy carriers include the Kassø E-Methanol plant in Denmark (42 ktpa e-methanol ad 8 ktpa H_2 from 52 MW electrolysers) [40]. An important project for blue hydrogen and ammonia production is the plant near Kashiwazaki, Japan, commissioned in 2025 and planned production of 700 tpa of ammonia [59].

Relevant for mines is also local hydrogen production in microgrids. Although there are not numerous commercial sites, the coupling of off-grid hydrogen technologies and renewable electricity has been demonstrated in several pilot and demonstration projects. The most relevant for mining is the demonstration of the nuGen 510-ton hydrogen-battery hybrid Mining Truck [98], where a 3.5 MW Alkaline electrolyser, an 800-kg compressed hydrogen storage (500 bar) and a hydrogen dispenser has been installed in the Mogalakwena mine in South Africa [60]. In Australia one can mention the Denham Renewable Hydrogen Microgrid, with 704 kW solar power, 348 kW electrolysis, compressed hydrogen at 300 bar and a 100-kW fuel cell [61]. The EU-funded project REMOTE demonstrated small microgrids using power-to-power hydrogen systems using local renewables in several locations in Europe (Italy, Norway, Greece) [62]. The cost of hydrogen production is region-dependent and varies due to different methods and energy costs, with tools available to estimate levelized costs [63]. Beyond cost, a holistic evaluation of production methods is needed [64,65], with large-scale green hydrogen from electrolyzers and blue/turquoise hydrogen from natural gas seen as near-term solutions, while long-term demand may require solar-based electrochemical or thermochemical production [66]. For local production, alkaline and PEM electrolyzers powered by renewables are most viable, though emerging technologies could play a role, and valorizing by-products like heat and oxygen can improve profitability [67], particularly in mining. Infrastructure scaling, intermittent operation, and energy sourcing challenges must be addressed as well, with green hydrogen relying on new or surplus renewables to ensure low-carbon standards.

3.2. Hydrogen transportation and storage

Efficient hydrogen transportation and storage are critical elements in the successful implementation of hydrogen-based energy systems for mining operations. After hydrogen is produced, the primary challenge is determining the most suitable method to transport it from the production site to the mining site and the method to store it. This section evaluates several transportation and storage methods, considering their strengths, weaknesses, and applicability to mining operations, particularly in relation to distance, volume, and infrastructure. Hydrogen can be transported via pipelines, trains, tanker trucks, or ships, depending on the form and distance involved. Multiple hydrogen carriers and storage forms are used, including compressed gaseous hydrogen (CGH_2), liquid hydrogen (LH_2), cryo-compressed hydrogen (CcH_2), liquid organic hydrogen carriers (LOHC), and ammonia (NH_3) [68], see Table 3.

For mining operations where hydrogen is produced on-site, the simplest and most widely used method involves compressing the hydrogen to pressures of 250–500 bar [69] and transferring it between storage and refueling stations using fixed pipelines. Hydrogen distribution technologies, including the selection of materials resistant to hydrogen embrittlement, are well-established and mature [70,71]. This method assumes minimal additional infrastructure beyond what is needed for hydrogen production and storage. It is effective for short-distance transport, as hydrogen compression allows relatively straightforward handling. CGH_2 is most used in this setup.

For larger distances or larger volumes, more complex transportation methods must be considered. The volumetric density of hydrogen is low, even when compressed, which requires the exploration of alternative methods to increase energy density and improve transport efficiency. Several strategies are available, each with its own trade-offs in terms of

Table 3
Overview of hydrogen transport and storage options.

Form/Carrier	Abb.	Transport Option	Storage Type	Key Features	Challenges
Compressed Gaseous Hydrogen	CGH_2		High-pressure cylinders (250–500 bar)	Mature technology, effective for short distances	Low energy density
Liquid Hydrogen	LH_2		Cryogenic tanks (−253 °C)	High energy density, large-scale and long-distance transport	High liquefaction energy demand
Cryo-compressed Hydrogen	CcH_2		Combined high-pressure and cryogenic	Higher density than LH_2	Technically complex, not widely commercialized yet
Liquid Organic Hydrogen Carriers	LOHC		Ambient liquid tanks	Operates at ambient conditions, compatible with existing fuel infrastructure	Energy-intensive dehydrogenation, catalyst cost
Ammonia	NH_3		Pressurized or refrigerated tanks	Very high hydrogen density, existing infrastructure	Toxicity, complex reconversion to hydrogen

cost, complexity, and logistics [72,73]. One of them is well established method of liquefaction, where hydrogen is cooled to −253 °C. This process allows hydrogen to be transported at ambient pressures, offering higher energy density than compressed hydrogen. However, liquefaction is energy-intensive, requiring 13.8 kWh/kg for cooling, and requires robust insulation to prevent boil-off [74]. LH_2 can be transported over long distances using specially designed cryogenic tanker trucks, trains, or ships. An alternative is CcH_2, which combines liquefaction and compression to further increase storage efficiency.

Another well-known method is industrial transport medium ammonia (NH_3) with a high energy density (12.7 MJ/l). It can be converted back into hydrogen, but this conversion process incurs significant costs and poses challenges related to its toxicity and handling [75–79]. Further on, LOHC, e.g. dibenzyltoulene, offer a liquid-state hydrogen transport solution that can operate under ambient conditions. These systems are compatible with existing fuel infrastructure and use a closed-loop process with dehydrogenation occurring at 260–310 °C [75]. However, the process of releasing hydrogen from LOHCs requires additional energy, and the organic carrier must be transported back to the producer. Moreover, organic fuels, e.g. formic acid and methanol, can serve as carriers for hydrogen, leveraging existing infrastructure. However, they require renewable carbon sources for low-carbon hydrogen production, as they release CO_2 during dehydrogenation [80–82].

Transporting hydrogen efficiently is a major challenge in developing a sustainable hydrogen economy, with different methods varying in cost, energy demand, and infrastructure requirements. A study on hydrogen transport in Europe [83] explores various scenarios, with large-scale point-to-point transportation of 1 million tons of hydrogen being the most relevant. The study highlights the high energy demand for dehydrogenation at the receiving site, making compressed or liquefied hydrogen more suitable when energy availability is limited. Among the options, liquid hydrogen stands out as the most cost-effective for large-scale transport, as its higher liquefaction costs are balanced by lower transportation expenses. The optimal transport method depends on energy availability at the destination and overall cost efficiency.

On-site storage solutions vary depending on hydrogen transport. A refueling station with CGH_2 storage is the most common option, while LH_2 storage and refueling stations become relevant when liquid hydrogen is transported or required [84,85]. If alternative energy carriers like NH_3 are utilized, specific storage methods such as compressed or refrigerated systems are typically employed [85]. Additionally, when hydrogen is produced on-site using non-dispatchable renewable energy sources, implementing seasonal or long-term storage becomes crucial to ensure a continuous and reliable hydrogen supply for mining operations [1,19]. Advanced storage solutions like CcH_2 and LOHCs may also offer opportunities for flexible integration into mine site energy systems.

When having a look at deployment of hydrogen transport, there are 37 000 km of hydrogen pipelines planned for 2035, although less than 6 % has reached Final Investment Decision, and most projects in Europe [41]. For local distribution, there were by the end of 2024 1160H_2 refueling stations operating in the whole world, mostly in East Asia and Europe [86]. Underground storage is rather limited; from the 11 TWh H_2 announced by 2035, only 5 % has reached final investment decision and the main projects are in Europe: Germany, Austria and United Kingdom. The International Energy Agency sees also a tight connection between hydrogen production and export, with 45 % of low-emissions hydrogen coupled with export (16 Mtpa H_2-eq is planned by 2030 although only 5 % of export-oriented projects have reached investment stage). Out of the 130 high-traffic ports that may have access to minimum 130 ktpa of low-emissions hydrogen within 500 km, 55 have significant nearby hydrogen supply and high infrastructure readiness, although handling methanol and ammonia requires a clean source of carbon and large space for safety respectively. For the case of LOHC, the main advantage is the possibility to use existing chemical and oil product logistics chains [41].

Some important operational projects for transport and storage of hydrogen and related energy carriers include the Brünsbuttel ammonia import terminal in Germany, with a 3 mtpa ammonia import capacity [40]. For storage, an important example of salt cavern hydrogen storage in operation is the Hydrogen Pilot Cavern Krummhörn, with a capacity of 500 000 Nm^3 H_2 or 1,8 GWh [87]. The port of Rotterdam is also making considerable progress on building a hydrogen system for multiples energy carriers and uses, including ammonia bunkering or large-scale carbon capture and storage, with several other projects announced [88].

Various options exist for producing, transporting, and storing hydrogen for use in mine. Key factors such as distance, grid connection, hydrogen demand, intended applications, required carriers, and available renewable resources significantly influence the choice of the optimal solution. Since no single approach meets all needs, a case-by-case analysis is essential to identify the most suitable hydrogen supply strategy for each mining site. Future advancements in hydrogen infrastructure, along with ongoing research into alternative transport mediums, will continue to shape the most efficient and sustainable solutions for the mining sector.

In conclusion, selecting a hydrogen supply chain for mining is a critical decision shaped by significant hurdles that differ across pathways. Cost remains the primary barrier, with green hydrogen produced via electrolysis (EL) still two to three times more expensive than conventional grey hydrogen due to the high capital expenditure of electrolyzers and the cost of renewable electricity. Steam methane reforming (SMR) with carbon capture and storage (CCS) (SMR with CCS, or blue hydrogen) offers a lower-cost, low-carbon alternative but is limited by the availability of suitable CO_2 storage sites and the extensive infrastructure needed for carbon transport and sequestration. Safety challenges also vary: compressed hydrogen gas requires managing high pressures and embrittlement risks, liquid hydrogen (LH_2) relies on complex cryogenic systems to prevent boil-off and flammability, and carriers such as ammonia (NH_3) present toxicity risks that demand new handling protocols. The most pervasive challenge, however, is the infrastructure gap, as the lack of pipelines, refueling stations, and standardized equipment certification forces reliance on costly, logistically complex trucked-in hydrogen, particularly problematic for remote mine sites. Addressing these barriers through technological innovation, policy support, and tailored site-specific planning is essential for hydrogen to become a viable energy vector in the mining sector.

4. Hydrogen use in mining

The mining industry is undergoing a transformative shift toward hydrogen-based energy solutions to achieve carbon neutrality and reduce reliance on fossil fuels. Several leading mining companies worldwide are investing in hydrogen projects and have set ambitious targets to integrate hydrogen technologies across various applications, aiming to significantly reduce their carbon emissions by 2030 and 2050. Key developments include on-site hydrogen production, the deployment of fuel cell-powered excavators and haul trucks, and the integration of hydrogen fuel cells into mining infrastructure. Furthermore, hydrogen-powered long-haul trucks, already in use in other industries, hold great potential for reducing emissions in mining-related material transport. These advancements not only drive decarbonisation but also enhance energy security, lower operational costs, and position hydrogen as a cornerstone of sustainable mining.

4.1. Hydrogen related projects in the mining industry

An overview of significant hydrogen-related projects led by key mining companies and groups is provided in Table 4.

Fortescue Metals Group (FMG) is pioneering the adoption of green hydrogen at its Green Energy Hub in Christmas Creek, Australia, utilizing 700 kW electrolysers powered by solar energy to produce 1500 tons of high-purity green metal annually [89]. Additionally, FMG is developing large-scale hydrogen projects in Norway and advancing trials of hydrogen-powered blasthole drill rigs and haul trucks [90]. Rio Tinto, in partnership with H2 Green Steel, is replacing coal with green hydrogen in iron ore reduction processes, targeting a 95 % CO_2 reduction at its Swedish facility by 2025 [91]. The company is also piloting hydrogen-fueled calcination at its Yarwun alumina refinery, integrating a 2.5 MW PEM electrolyser to produce 300 tons of hydrogen annually for process heating [92]. Similarly, Glencore Raglan Mine has implemented a hydrogen-integrated microgrid in Arctic Canada, combining a 3 MW wind turbine with fuel cells and battery storage to power remote mining operations [93]. The Hydra project in Chile, led by ENGIE and Mining3, is testing 100–200 kW hydrogen fuel cells in a haul train under high-altitude conditions, setting performance benchmarks for hydrogen-powered mining locomotives [94]. Steel manufacturers such as ArcelorMittal are also transitioning to hydrogen-based direct reduction in steelmaking, with pilot projects underway in Germany [95]. Other key players, including Australian Vanadium [96], Ivanhoe Mines [97], and Macarthur Minerals [98], are investing in hydrogen electrolysis, storage, and carbon capture technologies, positioning hydrogen as a central pillar in the mining sector's decarbonisation strategy. section 3.2. elaborates more on the heavy-duty vehicles powered by hydrogen fuel.

Table 4
Hydrogen related projects in mining.

Mining companies and groups	Hydrogen-related project	Ref.
Fortescue Metals Group	Green Energy Hub in Australia (solar-powered electrolysers), large-scale projects in Norway, and hydrogen-powered drill rigs and haul trucks.	[89,90]
Rio Tinto, H2 Green Steel	Green hydrogen in iron ore reduction (95 % CO_2 reduction by 2025), and hydrogen-fueled calcination at Yarwun alumina refinery.	[91,92]
Glencore Raglan Mine	Hydrogen-integrated microgrid in Arctic Canada (wind turbine, fuel cells, and battery storage).	[93]
ENGIE and Mining3	Hydra project in Chile (hydrogen fuel cells in haul trains for high-altitude mining).	[94]
ArcelorMittal	Hydrogen-based direct reduction in steelmaking (pilot projects in Germany).	[95]
Australian Vanadium Ivanhoe Mines Macarthur Minerals	Investment in hydrogen electrolysis, storage, and carbon capture.	[96–98]

4.2. Hydrogen powered heavy duty vehicles

Hydrogen fuel cell technology is progressively being tested in heavy duty off-road mining vehicles. Demonstration and test runs are mostly common vehicles conducted on excavators weighting 20–30 tons [99–101] and mining trucks with a payload range between 251 ton and 320 ton [102–108]. Table 5 provides an overview of all on-going initiatives taken by vehicle manufacturers, engine and power system developers and industrial giants across the globe. The table first presents excavators, ordered from the highest to the lowest technology readiness level (TRL), followed by mining trucks.

Excavators like the R 9400 E from Liebherr and Fortescue, Volvo 300E Excavator, 220X Excavator and Komatsu-Toyota H2 Excavators demonstrates a significant leap forward in sustainable machinery for mining. The substitution of diesel engines with hydrogen fuel cells eliminates direct emissions of CO_2 and particulate matter, addressing stringent environmental and occupational health standards. The energy density of hydrogen, combined with the efficiency of PEM fuel cells, offers comparable or superior performance to traditional systems while reducing dependency on ventilation systems in enclosed environments [99]. Moreover, fuel cells provide the dual advantage of extended operational autonomy and rapid refueling, crucial for high-demand, continuous-use scenarios in remote or underground sites. TRL of these machines vary based on several key factors, including infrastructure readiness, regulatory framework, and integration with existing mining operations. Initiatives by JCB [100] and Komatsu [101] fall within TRL 3 to 6, while Liebherr and Fortescue and also Ballard and Applied Hydrogen currently leads in this field [99].

In terms of mining trucks, the Europa, the Komatsu 930E Mining Truck and the nuGen 510-ton Mining Truck have achieved TRL 6 through successful demonstrations, showcasing significant advancements in hydrogen-powered engines. Fortescue's Europa is a T 264 Liebherr haul truck and contains a 1.6 MWh battery (developed in-house by Fortescue WAE) and 500 kW of fuel cells. The prototype can store more than 380 kg of liquid hydrogen [103]. Once commissioned on site (remote location, extreme climate, excessive dust), Europa will be refueled with liquid hydrogen from a gaseous and liquid hydrogen plant, located at Fortescue's Green Energy Hub at Christmas Creek [102]. The Komatsu 930E Mining Truck, with a 320-ton payload capacity, is equipped with General Motors HYDROTEC fuel cell technology, eliminating CO_2 emissions while maintaining high operational performance [104,105]. The nuGen 510-ton Mining Truck, with a 290-ton payload capacity, is part of Anglo American's Zero Emissions Haulage Solution and features a 2 MW hybrid powertrain combining hydrogen fuel cells and battery technology. A key demonstration site for this truck is the Mogalakwena mine in South Africa, where Anglo American has integrated renewable hydrogen infrastructure, including on-site solar-powered hydrogen production and refueling. This initiative aims to achieve total operating costs comparable to diesel by 2030 while reducing emissions in open-pit mining by up to 70 %, decreasing reliance on imported fuels, and creating cost-saving opportunities for operators [106–108].

Table 5
Hydrogen powered heavy duty mining vehicles.

Vehicle's image, name and manufacturer		Vehicle weight/Payload	TRL	Ref.
	**R 9400 E Excavator** (Liebherr and Fortescue)	n.a.	7	[109,110]
	**Volvo 300E Excavator** *(Ballard, Applied Hydrogen)*	30 ton	7	[99]
	**220X Excavator** *(JCB)*	20 ton	6	[100]
	**Komatsu–Toyota H2 Excavator** *(Komatsu)*	Medium sized	3	[101]
	**Europa** *(Fortescue)*	251 ton payload	6	[102,103]
	**Komatsu 930E Mining Truck** *(General Motors, Komatsu)*	320 ton payload	6	[104,105]
	**nuGen 510-ton Mining Truck** *(Anglo American)*	290 ton payload	6	[106–108]

4.3. Potential use of hydrogen long-haul trucks in mining

Hydrogen-powered long-haul trucks are emerging as viable alternatives to diesel-fueled heavy-duty transport, with several manufacturers, investing in fuel cell and hydrogen internal combustion engine (H2-ICE) technologies, see Table 6.

Daimler's GenH2 truck, with a gross combination weight (GCW) of 40 tons, utilizes liquid hydrogen fuel cells to achieve extended driving ranges comparable to diesel counterparts, making it suitable for long-haul transportation [111]. Similarly, Ashok Leyland has developed the 4125 HN fuel cell electric truck and the 4120H2-ICE truck, both designed for high payload capacities and improved efficiency [112, 113]. Tata Motors' Prima E.55S and H.55S, featuring a hydrogen fuel cell system and internal combustion system respectively, both with a range of 350–550 km, further underscores the sector's commitment to zero-emission transport [115,116]. The prototype of hydrogen fuel cell powered Eicher Pro 3015, developed by Volvo Eicher Commercial Vehicles (VECV), was showcased in Auto Expo 2023 which makes it a TRL 4 vehicle [118–120]. The vehicle is designed for 19-ton gross vehicle weight (GVW) to support medium duty freight applications with reduced environmental impact. These hydrogen-powered trucks hold significant potential as bulk carriers in the mining industry, where materials such as ore, coal, and aggregate must be transported efficiently over long distances. The adoption of hydrogen fuel in mining transportation can reduce operational emissions, minimize fuel costs, and integrate with on-site hydrogen production facilities, creating a sustainable supply chain for large-scale resource extraction operations.

4.4. Economic feasibility overview

The cost of implementing hydrogen-powered mining machinery compared to diesel alternatives has been widely studied [122]. found that hydrogen-powered trucks are 20–68 % more expensive than diesel, with hydrogen fuel costs ranging from \$6.6–11/kg in Europe and \$5.5–6.6/kg in China. High vehicle costs, hydrogen prices, and infrastructure gaps prevent competitiveness today, compound by uncertainties in technology maturity and policy support. However, the study projects that with hydrogen prices falling below \$4–5.5/kg, cost parity may be achievable after 2035, particularly under strong incentives.

Techno-economic Assessment (TEA) conducted by Ref. [123] on green hydrogen production for a Chilean mining operation suggests that a small-scale system for blending hydrogen with diesel is not viable, with average levelized cost of hydrogen (LCOH) around \$6.1/kg H_2 and

Table 6
Hydrogen powered long-haul trucks in the market as potential use in mining.

Vehicle's image, name and manufacturer		Fuel option; Vehicle weight/Payload; Other specifications	TRL	Ref.
	**Mercedez-Benz GenH2 Truck** (Daimler Truck)	H_2 fuel cell with 2 × 150 kW + battery with 400 kW; 25 tons payload	7	[111]
	**Ashok Leyland 4120 H2-ICE Truck** (Ashok Leyland)	H_2 ICE; 40.5 ton GVW; 184 kW (250 hp)	6	[112–114]
	Ashok Leyland 4125 HN Truck (Ashok Leyland)	H_2 fuel cell, 120 kW PEM cell; 41 ton GVW, 250 hp	6	
	**Tata Prima E.55S & H.55S Truck** (Tata Motors)	H_2 ICE & H_2 fuel cell; 55-ton GVW; 350–550 km range	6	[115–117]
	**Eicher Pro 3015 Truck** (VECV)	H_2 fuel cell; 19-ton GVW; 400 km range	4	[118–121]

a negative net present value (NPV) (-$47,645). In contrast, a medium-scale project using hydrogen for fuel cell trucks achieved LCOH of $5.6/kgH$_2$ and a positive NPV ($ 379 016), reducing approximately 800 tons of CO_2 annually. Key cost drivers included electrolyzer capital costs, efficiency, photovoltaic (PV) plant investment, and compression costs. This study concludes that medium-scale hydrogen adoption is feasible and scalable, supporting Chile's mining decarbonisation goals.

Comparative analysis by Ref. [124] also indicates that hydrogen-fueled heavy trucks cost higher than pure electric and diesel-fueled vehicles based on accessibility and production cost of energy carrier. Their study evaluated the competitiveness of the trucks in mining scenarios over five years where the total costs were estimated at $54,200, $47,800 and $58,500 for diesel, pure electric and hydrogen trucks respectively. Hydrogen showed lower fuel costs than diesel but suffered from very high infrastructure costs. Subsidies may reduce purchase price but do not close the gap. Competitiveness improves in regions with cheap hydrogen by-product, where costs approach diesel levels. Overall, hydrogen trucks are not yet cost-competitive but could become viable with regional advantages and strong policy support.

[125] analyzed the total cost of ownership (TCO) of fuel-cell long--haul trucks (FCETs) in Europe and compares them with diesel counterparts, using a 5-year first-user model. It aims to assess economic feasibility across seven major European markets (France, Germany, Italy, Spain, the Netherlands, Poland, United Kingdom and identified policy pathways to make FCETs competitive. In the analysis purchase cost, residual value, fuel, maintenance, tolls and taxes are considered. Hydrogen was assumed to be produced onsite via renewable electrolysis and compressed to 700 bars, with fueling station costs included. By 2030, retail price gaps with diesel narrow to about $66,00 but hydrogen fuel cost remains decisive: expected prices of $5.5-$8.8/kgH$_2$ exceed the break-even threshold of $3.9-$5.5/kg H_2. Closing the gap required $1.3-$4.4/kgH$_2$ subsidies, e.g. road-toll exemptions, and stricter CO_2 standards.

[36] assessed hydrogen-powered vehicles and highlighted heavy-duty trucks as the most promising application. Hydrogen trucks benefit from ranges of 400–600 km, refueling times of 10–15 min, and load capacities comparable to diesel, making them suitable for long-haul and intensive operations. However, they face barriers including energy efficiency of ~30 % (well-to-wheel), hydrogen costs above $5–8/kg, and sparse refueling networks. Competitiveness improves if hydrogen prices fall below $4/kg and refueling infrastructure expands. The study concludes that hydrogen trucks could achieve large-scale adoption if supported by policy incentives, renewable hydrogen supply, and coordinated infrastructure investment.

In an academic study [126] hydrogen's potential for construction equipment as an alternative to diesel has been examined. They also indicate the costs as an obstructing factor between the two fuels where hydrogen cost in 2020 was $6.6–11/kg, much higher than diesel. Competition requires prices below $4.4–5.5/kg, along with advances in electrolyzers and refueling networks. The study concludes that hydrogen is promising for heavy-duty construction machines but is unlikely to achieve economic viability until after 2030, dependent on strong policy support.

Studies consistently show that hydrogen-powered trucks and machinery are not yet cost-competitive with diesel or electric alternatives, mainly due to high vehicle prices, fuel costs of $5.5–11/kg, and limited refueling infrastructure. TEAs [123] demonstrate that small-scale hydrogen blending is uneconomical, while medium-scale fuel cell truck adoption in mining can be viable under favorable conditions, with LCOH at $5.6/kg and positive NPV. Comparative analyses [124,125] indicate hydrogen trucks remain more costly than diesel and electric, though competitiveness improves with hydrogen cost below $4–5.5/kg and policy incentives. Reviews [36,122,126] converge that large-scale viability is unlikely before 2030, requiring cheaper hydrogen, advances in electrolyzers, expanded infrastructure, and strong regulatory support.

Adopting hydrogen in mining operations would initially increase production costs of mineral products due to high hydrogen fuel prices (USD 5.5–11/kg) and infrastructure expenses. Fuel typically represents 15–25 % of mining Capital Expenditure (OPEX) [127], meaning hydrogen substitution could raise overall costs by 3–5 % per ton of concentrate compared to diesel. Studies [122–126] converge that cost competitiveness requires hydrogen below USD 4–5.5/kg, achievable after 2030 with technology progress and policy incentives. Long term, hydrogen adoption could stabilize or reduce final product prices through avoided carbon taxes and improved environmental performance.

5. Hydrogen safety in perspective of mines

Ensuring safety is crucial when integrating hydrogen technology as an alternative to fossil fuels in the mining industry. This section addresses the multi-layered safety challenges associated with this transition. From the inherent risks of traditional mining to the specific hazards associated with the use of hydrogen and its integration into mining processes, understanding, and addressing these challenges are essential. This section also examines past incidents, current risk mitigation technologies and the regulatory framework to protect personnel and infrastructure in mining.

5.1. Safety challenges

Mining involves many hazards, including cave-ins, roof falls and risks associated with explosives and blasting. Fires and explosions from gases such as methane, respiratory problems from dust and fumes, and injuries from heavy machinery in confined spaces are common hazards too. In addition, miners are at risk from falls, noise, vibrations and exposure to toxic chemicals [128–134]. These existing challenges underscore the importance of carefully considering the integration of hydrogen given its flammability and the complex safety dynamics in mines.

Hydrogen poses several risks that need to be carefully managed. One of the main problems is the risk of explosion that can occur when hydrogen mixes with atmospheric oxygen within a wide concentration range 4–75 % and encounters an ignition source [135]. Next, the almost invisible flame of burning hydrogen adds to the danger as it is difficult to see in daylight. The small molecular size of hydrogen makes it susceptible to leaks, allowing it to escape from pipes and other structures more easily than denser gases. This permeation can also cause materials to become brittle, necessitating the use of special materials for storage. In addition, hydrogen can interfere with carbon monoxide alarms, so careful calibration is required to avoid false readings. Because hydrogen is lighter than air, it tends to accumulate in gas pockets near ceilings, creating hidden risks in enclosed spaces. Since hydrogen has no color or odor, it is imperceptible to humans, making it difficult to detect leaks and increasing the potential for unnoticed hazards [136]. This section focuses on hydrogen in gaseous form, as the machines currently use fuel cells working on gaseous hydrogen. Even using hydrogen carriers for transport or storage, such as ammonia or methanol, hydrogen must be converted to gas hydrogen to use it as a fuel. However, in the case of using those carriers, additional hazards may be present.

The integration of hydrogen into mining presents a unique set of challenges that compound both traditional mining risks and the specific hazards of hydrogen itself. One of the most pressing issues is adapting existing safety protocols to the unique properties of hydrogen. To address these challenges, mining operations must adopt a comprehensive approach that combines advanced technology and specialized training.

- Since hydrogen is highly flammable and can easily form explosive mixtures, it is critical that mining operations employ improved monitoring systems to detect even the smallest leaks. This requires the use of advanced sensor technology capable of accurately determining hydrogen concentrations in real time. Adequate ventilation systems should also be provided to ensure the safe dispersion of hydrogen and reduce the risk of explosive atmospheres.
- The infrastructure used for conventional mining may not be compatible with hydrogen systems, requiring significant investment in technology and materials to ensure safe integration. The risks of material degradation and embrittlement are associated with hydrogen exposure, further complicated infrastructure design and maintenance.
- Training personnel to recognize and respond to hydrogen-specific hazards is of paramount importance, as traditional mining safety training may not cover the unique challenges posed by this gas. Workers must be trained to eliminate ignition sources and ensure that equipment is grounded and properly maintained to prevent sparks.
- The logistical challenges of transporting hydrogen to and within the mine lead to additional safety considerations. There is a need to ensure that transportation routes do not expose workers to potential hazards, and robust safety measures must be put in place to prevent accidents during the delivery and storage of hydrogen.

By incorporating these elements into risk assessment, mining operations can develop a proactive strategy to manage complexity of hydrogen integration into mine and ensure a safe working environment.

5.2. Past incidents

The worst mining disaster in history occurred in 1942 in Benxi, China, where a fire in a coal mine, followed by the release of carbon dioxide, resulted in the deaths of 1549 workers [137]. This tragic event underscores the importance of safety measures in industrial operations. Similarly, in the context of hydrogen, a hydrogen incident is defined as the undesired events arise from the hydrogen leakage and hydrogen burns or explodes with substantial amount of energy released during the process of production, storage, transportation, and utilization of hydrogen [136,138]. Investigating and summarizing previous safety incidents involving hydrogen can make an important contribution to the development of safety regulations that should effectively prevent a repetition of similar incidents [139,140].

Recent studies on hydrogen accidents have been conducted by academic and industrial institutions. The European Hydrogen Incidents and Accidents Database 2.1 has been created to share lessons and data for risk assessment [141]. A study analyzing 120 hydrogen incidents (1999–2019) from the US Department of Energy found that laboratories are the most accident-prone locations (38 %), followed by hydrogen refueling stations (11 %) and commercial facilities (9 %). Common failures involve piping, valves, and storage devices due to hydrogen embrittlement. Equipment failure (36 %) is the main cause of incidents, followed by human error (14 %) and design faults (12 %). Most accidents result in property damage (42 %), with 10 % leading to injuries and 5 % to fatalities. Fatalities in hydrogen accidents are twice as high as in natural gas accidents [142].

Hydrogen technology in mining is still emerging, with no major incidents reported. However, hydrogen incidents relevant to mining sector are highlighted across four areas: production, transportation, storage, and applications [141]. These incidents, although not directly from mining sites, offer valuable lessons for the sector as it begins to adopt hydrogen-based solutions. In 2019, South Korea experienced a severe explosion at a renewable hydrogen production facility. The accident, caused by a buffer tank failure during an experimental setup, led to several fatalities and significant infrastructure damage. This highlights the risks associated with early-stage production technologies and underscores the need for stringent safety measures from the outset. That same year in Belgium, a fire broke out following the accidental damage of an underground hydrogen pipeline during excavation works. While no injuries were reported, the incident emphasizes the importance of accurate infrastructure mapping and safe excavation practices – particularly relevant to mining environments where subsurface operations are common. In 2021, Norway reported a hydrogen leak during a storage test, releasing 224 m^3 of gas. The source of the leak was traced to a flange connection with loose bolts, which was promptly corrected through maintenance. This case underscores the significance of routine inspection and proper assembly of high-pressure storage systems. Lastly, in 2023, a hydrogen truck in the Netherlands developed a leak due to a faulty valve with inadequately tightened bolts. Although it posed no immediate danger, it illustrates how small mechanical oversights can compromise hydrogen system integrity. Collectively, these examples offer key insights for mining operations, where the adoption of hydrogen technologies must be accompanied by robust engineering design, safety protocols, and continuous monitoring to ensure safe and reliable implementation.

5.3. Technology for hydrogen safety

To address the hazards posed by hydrogen, manufacturers of fire and gas detection systems work within the construct of layers of protection to reduce the incidence of hazard propagation. Under such a model, each layer acts as a safeguard, preventing the hazard from becoming more severe. Fig. 2-a illustrates such a layered protection sequence for mitigating risk associated with hydrogen gas leaks [143]. There is a need to develop technologies and find ways to make mines hazard-free [144].

Hydrogen sensors are crucial for safety, detecting explosive mixtures with air and preventing explosions across hydrogen production and use [147]. In underground mines, they continuously monitor air quality and enable quick responses. These sensors activate shutdown systems, alarms, ventilation, and alert responders, ensuring compliance with safety regulations. Key factors for using sensors include protection against explosions, meeting performance requirements for flammable gas detection, and adhering to safety standards for electrical systems. Essential considerations include performance, lifetime, reliability, and cost [148]. Further requirements such as robustness, size and complexity are summarized in Ref. [149], providing a detailed overview of the key factors for consideration. Various hydrogen detection technologies, such as catalytic, electrochemical, and semi-conductive metal-oxide sensors, offer different advantages depending on application conditions [147,148,150,151]. The growing market provides a variety of sensors, such as continuous monitoring systems and multi-gas detectors [151], see Fig. 2-b.

Ventilation technology is crucial for mitigating hydrogen hazards in enclosed spaces, such as underground mines and hydrogen processing rooms on vessels. Proper ventilation prevents dangerous hydrogen accumulation, with strategies like overhead and opposite-side ventilation aiding vapor removal [152]. Testing hydrogen sensors and ventilation systems, along with evaluating risk in confined spaces, enhances safety protocols. The installation of hydrogen ventilation systems, such as those by HySA Infrastructure, see Fig. 2-c, demonstrates advancements and effective implementation in the industry [146]. Hydrogen gas leaks in vehicles pose a significant hazard that requires proactive response strategies. In this manner, computational fluid dynamics analysis was performed to develop effective countermeasures and point out the potential exposure of first responders to vapor cloud explosions. The use of blowers reduces the risk of explosion and improves readiness for the increasing use of hydrogen vehicles [153].

Other studies emphasize the importance of being prepared for emergencies in underground mines and responding quickly and effectively to hazards such as fires, explosions, and flooding. Mine rescue teams and comprehensive training protocols are central to worker survival, especially self-rescue preparedness [154,155].

5.4. Regulations and standards

Ensuring safety in mining operations requires strict adherence to regulations and standards. Various countries have established comprehensive frameworks to promote safe mining practices. Notable examples include Mine Safety and Health Administration in United States of America, Mines Regulations 2014 in United Kingdom, Work Health and Safety Regulations 2012 in Australia, Work Environment Act 1977 in Sweden, Reglamento de Seguridad y Salud Ocupacional en Mineria 2011 in Peru, Mine Health and Safety Act 1966 in South Africa. In addition to the national regulations, the European Union has implemented key directives that play a vital role in maintaining safety in mining operations: Directive 92/91/EEC which sets out minimum requirements for improving the safety and health protection of workers in the mineral-extracting industries and Directive 2006/21/EC which regulates the management of waste from the extractive industries to prevent and reduce adverse effects on the environment and human health.

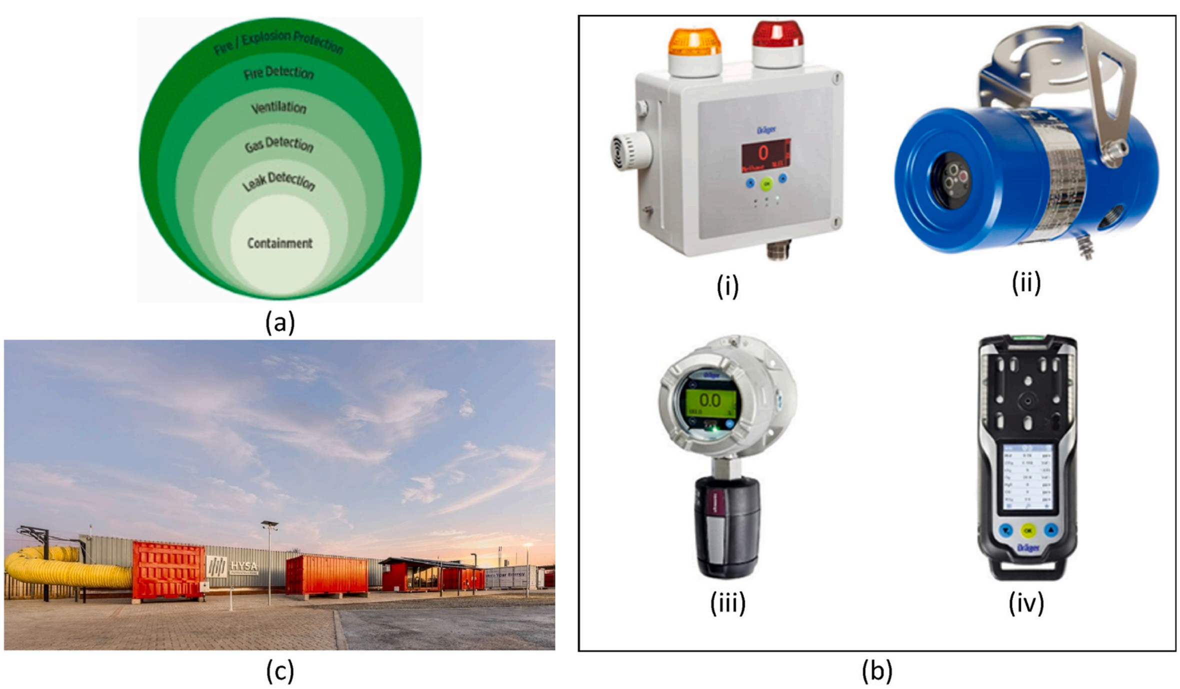

Fig. 2. *Hydrogen safety: (a) Layered protection sequence for mitigating risk associated with hydrogen gas leaks* [143], *(b) commercially available hydrogen sensors - (i)* a self-contained gas detection system for the continuous area monitoring of flammable gases in ambient air*, (ii)* hydrogen-based fires detection with its triple IR sensor*, (iii) ultrasonic gas leak detector, (iv) multi gas detector* [145] *and (c) hydrogen ventilation research site in North West of South Africa* [146].

The use of hydrogen in mining operations poses significant safety challenges, primarily due to its explosive nature. To mitigate these risks effectively, strict adherence to regulatory frameworks and international standards is essential. The EU Directives 2014/34/EU and 1999/92/EC provide a solid legal foundation, ensuring equipment and worker safety in potentially explosive atmospheres. In addition to these directives, adherence to international standards is paramount. International standards like IEC 60079:2024 ensure utmost safety for electrical equipment in explosive atmospheres. EN 1127 provides fundamental methods for explosion prevention, with EN 1127–2:2002 + A1:2008 focusing on mining environments. ISO/IEC 80079 series specify equipment safety, notably ISO/IEC 80079–38:2016 for underground mines, where rigorous safety measures are essential.

Furthermore, ISO 19880–1:2020 outlines general requirements for gaseous hydrogen fueling stations, ensuring their safe operation. Complementing this, ISO 19880–8:2019/Amd 1:2021 focuses on fuel quality control for hydrogen fueling stations, aligning with Grade D of ISO 14687 to ensure consistent hydrogen purity. ISO 14687:2019 specifies the quality standards for hydrogen fuel, which is critical for the performance and safety of hydrogen fuel cells. For hydrogen production via electrolysis, ISO 22734:2019 provides guidelines for industrial, commercial, and residential applications, covering hydrogen generators using water electrolysis. In addition, ISO 10156:2017 addresses the fire potential and oxidizing ability of gases and gas mixtures, essential for selecting appropriate cylinder valve outlets for safe storage and handling. ISO 26142:2010 specifies requirements for hydrogen detection apparatus in stationary applications, ensuring early detection of hydrogen leaks to prevent accidents. The CGA G-5.5-2021 standard provides design guidelines for hydrogen vent systems used in both gaseous and liquid hydrogen systems, emphasizing the importance of safe operation of these vents to mitigate risks associated with hydrogen release. Lastly, ISO/TR 15916:2015 offers basic considerations for the safety of hydrogen systems, providing a comprehensive overview of safety measures necessary to handle hydrogen effectively and safely.

6. Modelling the role of hydrogen in mines

In the modelling section the focus is on hydrogen modelling used in fuel cells and in the general energy system modelling for specific mining locations and regions where hydrogen plays an important role. Advancements in numerical modeling of hydrogen are an important element for the electrification of equipment and vehicles, discussed in Section 5.1. On the other hand, given the complex picture of energy availability, stationary and movable final energy use, several energy carriers and short- and long-term uncertainty in the mining sector, it is necessary to develop complex energy system models that can provide decision support in the most adequate decarbonisation strategies for the different mining sites. Thus, recent studies on the use of energy system modeling to assess the use of hydrogen in mining are presented in Section 5.2.

6.1. Numerical modelling of hydrogen as fuel

Modeling and simulation, encompassing computational fluid dynamics (CFD) and electrochemical models, have been crucial for evaluating and optimizing hydrogen-based power systems for mining applications, particularly in two key areas: hydrogen combustion in internal combustion engines (ICEs) and hydrogen fuel cell powertrains.

6.1.1. Hydrogen combustion in internal combustion engines

Numerical modeling of hydrogen combustion focuses on capturing the complex fluid dynamics and chemical kinetics inherent in hydrogen's rapid and wide-ranging combustion behavior. In mining, this is critical for ensuring that hydrogen ICEs operate reliably under extreme conditions such as high dust loads, temperature variations, and variable engine loads encountered in underground and open-pit operations. Numerical modeling of hydrogen combustion is crucial for understanding the complex fluid dynamics and chemical kinetics associated with its rapid burning characteristics. Hydrogen's high flame speed, low ignition energy, and wide flammability range present both advantages and challenges in combustion applications. CFD has been extensively used to optimize engine performance, including injection strategies, air-fuel mixing, and emissions control [156,157]. Furthermore, studies have developed models that simulate lean hydrogen combustion in turbocharged port fuel injection spark-ignition engines, addressing challenges such as flame instabilities, pre-ignition, and backfire [157]. Direct-injection engine simulations have analyzed the impact of nozzle hole numbers and injection timing on combustion efficiency [156]. Research has also examined hydrogen's effect on flame speed and burn rates in fuel mixtures, aiding in refining combustion chamber designs for better efficiency and reduced nitrogen oxides (NO_x) emissions [158]. Further modeling efforts have explored multiphase flow properties in hydrogen combustion, providing insights into optimizing ignition timing and fuel-air ratios for vehicles [159]. Also, high-compression ratio engine simulations have been utilized to predict performance gains in heavy-duty applications [160]. Other studies have incorporated control models for hydrogen-powered ICEs, integrating transient operating conditions and variable load cycles to optimize fuel efficiency and engine durability [161]. Simulation-based research has also evaluated the impact of exhaust gas recirculation and lean-burn strategies on NO_x emissions reduction while maintaining high thermal efficiency [162].

6.1.2. Hydrogen fuel cells

Hydrogen fuel cells offer a zero-emission alternative for powering mining equipment, necessitating numerical modeling to analyze system behavior under dynamic duty cycles. Simulations of PEM fuel cells have been employed to optimize thermal management strategies, ensuring proper cooling and water management to maintain efficiency [163]. Also, numerical studies have investigated hybridization techniques that integrate hydrogen fuel cells with auxiliary energy storage systems, such as batteries or supercapacitors, to handle peak power demands and regenerative braking energy [164]. System-level simulations have provided insights into powertrain efficiency, optimizing control strategies for fuel cell-powered haul trucks and underground loaders [165]. Research has examined the effects of hydrogen flow rates, stack temperature variations, and cooling system efficiency on overall fuel cell performance [166]. Furthermore, advanced multiphysics modeling has coupled electrochemical reactions with fluid dynamics and heat transfer processes, enhancing predictive accuracy for fuel cell degradation under mining conditions [167]. Hybrid powertrain configurations combining hydrogen fuel cells and internal combustion engines have also been numerically evaluated, demonstrating potential for increased operational flexibility and energy efficiency [168].

6.2. Decision support using energy system modelling in the mining sector

When selecting technologies for mining operations, careful consideration of various factors is crucial to ensure efficiency, sustainability, and cost-effectiveness.

- Firstly, the choice should account for available energy sources, including renewable options, e.g. hydro, solar, and wind, as well as nuclear and fossil-based grids.
- Understanding the logistics resources, such as electrical grids, pipelines, harbors, transportation networks, and storage capabilities, is essential for seamless operations.
- Regarding hydrogen, it is also imperative to assess its current usage, forms (compressed, liquid, ammonia, methanol), and the required transformations for integration into mining processes. Exploring hydrogen synergies with local industries and infrastructure can offer valuable insights into enhancing operational efficiency and

flexibility, especially in utilizing excess energy or leveraging low-temperature heat generated during mining operations.

By considering these points, mining companies can make informed decisions that optimize resource utilization and minimize environmental impact which are not trivial. Modelling energy systems and specific technologies can provide a good understanding of the advantages and limitations of replacing fossil fuels in mining operations. Energy models vary in scope and functionalities and can be classified in different ways. Several models are often needed to obtain a complete picture of a specific system [169].

Recently, a review on the state of the art and challenges of energy system modeling was performed [170]. One of the challenges is Renewable Energy Systems integration, where uncertainty handling, multi-scale time (short- and long-term) and spatial modelling are key aspects to consider. Also, multi-carrier and multi-sector energy systems have increased in importance [170]. Furthermore, energy behavior and energy transition dynamics were identified as the next frontiers of energy system modelling. Most of these aspects are relevant for the energy systems of mining operations which aim to rely on renewable energy integration and alternative energy carriers such as hydrogen. Examples of the interplay between energy carriers and technologies of such a system are shown in Fig. 3 [1,19].

The exploration of hydrogen integration into mining operations is assessed through a variety of studies that employ different methodologies, address diverse goals, and focus on distinct mine types and contexts.

These studies collectively highlight the versatility and potential of hydrogen to enhance sustainability in mining. Table 7 summarizes recent studies on decarbonisation of the energy system in the mining sector, mostly with a techno-economic perspective and, in some specific cases, with a larger focus on emission reduction.

These studies use different methods to evaluate the use of hydrogen in mining at a system level: some use a commercial software such as Hybrid Optimization of Multiple Energy Resources (HOMER) [1,19,171,174] or they develop own optimization models, using Mixed Integer Linear Programming (MILP) formulations [27,172], but also Mixed Integer Non-linear programming (MINLP) formulations [173]. Regarding the scope of the study and main objectives, it varies from study to study, although most of them analyze the techno-economic feasibility of hydrogen in mining, and some of them include an emission analysis, either as part of the optimization using multi-objective optimization [172] or as a secondary measurement after the economic assessment [1,171].

The scope of these studies also vary in reference to which part of the mine's energy system is included: these range from a portion of electric energy provided and alternative shipping technology for a whole mining regions in Chile [173], the whole mine's energy system (including electricity, heat and fuel) [19,27], only in the power system of the mine [171,172] or the power system and some hydrogen in trucks [1]. The scope varies also in terms of the type of mine and location. While some studies focuses on regional energy supply for the mining industry [173], one finds use cases of individual mines, both On- and Off-grid, extracting e.g. gold, coal and copper, located in Chile, Canada, Ghana and China.

Another perspective that differs considerably between the reviewed studies is the role of hydrogen that is considered. Hydrogen is an option only in some cases, and only as energy storage [172]. Others consider hydrogen not only as (seasonal) energy storage but also in dispatchable power generation [171,173]. Some analyses consider a broader role of hydrogen apart from storage and power generation, such as vehicle fuel or heating.

These studies show that integrating hydrogen into mine energy systems can be economically viable, especially when considering the declining costs of renewable energy technologies and potential carbon emission reductions [19,172,173]. For example [19], found that a renewable system with a hydrogen-powered fleet and hybridized battery/hydrogen storage can be the most economically viable option for open-pit mines. Also, a renewable design with a Battery/Hydrogen Storage (with Electrolysis and Fuel Cell) and hydrogen-powered fleet configuration returns to the most profitable case in the same study. A common conclusion of these studies is the importance of hybrid systems that combine hydrogen with other renewable energy sources like solar

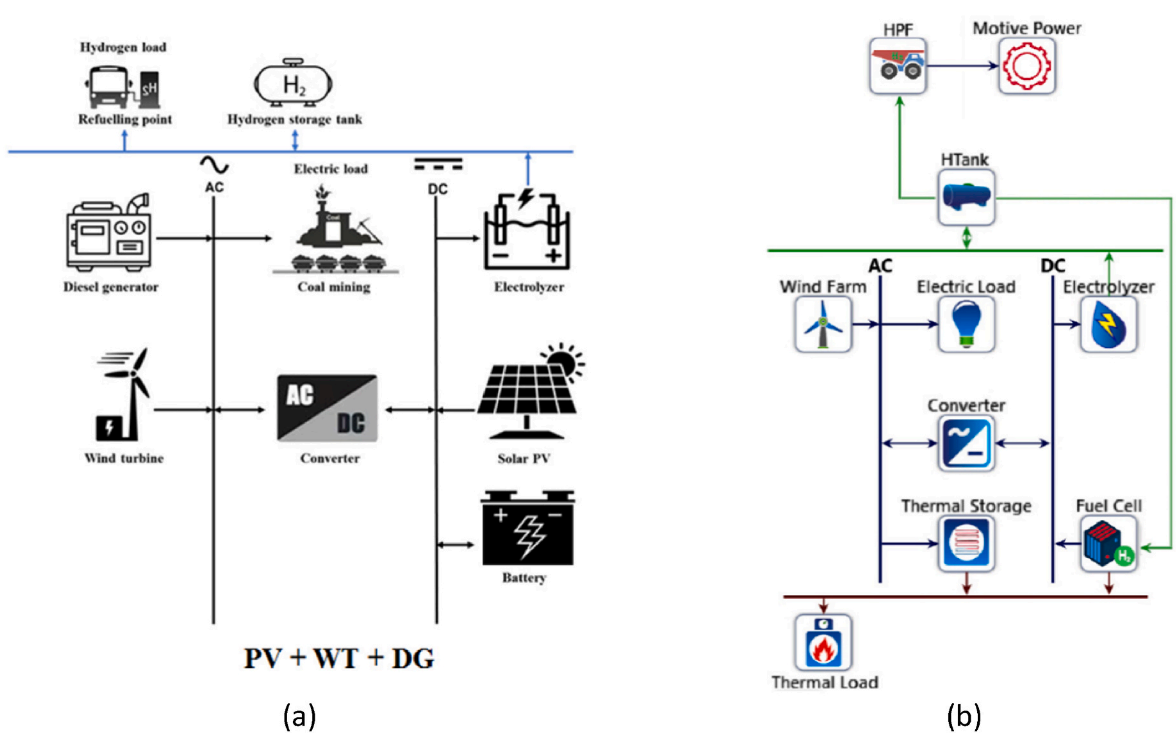

Fig. 3. Examples of modelling the role of hydrogen in mines: (a) Hydrogen is thought as an option to decarbonise truck transport using electrolysis and local hydrogen storage [1]; (b) Hydrogen is used as energy storage, to generate electricity and as fuel in haulage [19].

Table 7
Summary of recent literature that uses energy system models to evaluate hydrogen use in the mining sector.

Method	Objective and scope	Role of hydrogen	Type of mine	Ref.
HOMER	Economic and emissions analysis of different hybrid energy systems for power supply to the mine	Energy storage and power generation through fuel cells	Off-grid gold mine in Ghana	[171]
HOMER	Economic, technical, environmental feasibility study, social benefits of the electricity demand of mine and hydrogen load on trucks	Decarbonise truck transport using electrolysis and local storage	Coal mine in China	[1]
HOMER	Economic analysis (net present cost - NPC and levelized cost of energy - LCOE) compared to diesel of the total energy of mine (electricity, heat, haulage)	Storage, H_2 to electricity, H_2 as a fuel in haulage	Cold-climate open-pit mine in Canada	[19]
Optimization MILP model	Minimize total costs for the total energy supply of a mine	Seasonal storage, hydrogen engines, boilers and Fuel Cells	Off-grid arctic under-ground mine in Canada	[27]
Optimization MILP model	Multi-objective economic costs and emission minimization, considering only power demand of the mine	Energy storage in some cases	Grid-connected copper mine in Chile	[172]
MINLP	Optimization of net present value (NPV) of the supply of 10 % of mining industry electrical energy in the Antofagasta region in Chile, including photovoltaic sizing and Bound4blue wind technology on ships (optimizing the routes)	Used as fuel to provide dispatchable power to the mine	Whole mining region of Antofagasta region in Chile	[173]

and wind, along with energy storage solutions such as electric batteries, hydrogen and thermal storage [1,19,172]. Such technology combination addresses the variability of non-dispatchable RES and ensures a reliable energy supply for continuous mining operations [1,19]. In addition, hydrogen storage can be crucial to minimize the emissions of a mine's power system, like in Ref. [172]. The use of hydrogen in hybrid systems can significantly reduce greenhouse gas emissions (especially on-site) and reliance on fossil fuels, contributing to the decarbonisation of mining operations [1,19,172]. Nevertheless, the economic viability of hydrogen depends on factors such as the cost of renewable energy, the availability of resources, e.g. wind speed, solar radiation, and the specific energy demands of the mine [1,19,27]. Finally [173], points out the lack of regulations in certain areas to supportive policies and regulations to incentivize the adoption of sustainable energy sources, which will influence the different feasibility studies.

7. Future perspectives

The integration of hydrogen technology in mining offers strategic opportunities beyond technical innovation. Early adopters can gain a market advantage by positioning themselves as leaders in low-emission mining, enhancing their reputation and competitiveness. Supportive policy frameworks and government incentives can further accelerate technology development and adoption by providing funding, tax benefits, and regulatory guidance.

However, hydrogen adoption in mining faces several key technological barriers. Safety is a primary concern, particularly underground, due to hydrogen's flammability and limited quantitative risk analyses. Logistics and scalability also present challenges, including production, storage, transport, refueling infrastructure, and adaptation of fuel cells and electrolysers for large, continuous operations. Comprehensive life cycle assessments comparing hydrogen, batteries, and diesel are scarce but necessary, considering electrolyser production, hydrogen transport, energy losses, water use, and component recycling. Practical hurdles include fuel cell operation in dusty environments and the robustness of electrolysers with lower-purity water. Addressing these barriers is crucial for safe, scalable, and environmentally sound hydrogen deployment in mining.

Hydrogen technology, developed over decades in the oil and chemical industries, is now mature enough to enter another energy-intensive sector: mining. The first phase of integration is expected in open-pit mines, followed by underground operations due to safety and regulatory constraints. Mines with access to renewable energy sources such as wind, solar, and hydropower will have a particular advantage, and decreasing costs of both renewables and hydrogen will further support adoption. Hydrogen storage will be especially beneficial for mines with monthly or semi-annual operational cycles, while daily cycles may remain better served by battery storage. The growing number of pilot projects and deployment of machines such as excavators and haul trucks with technology readiness level 7–9 will accelerate adoption, reduce operational risks, and improve safety. Early implementations will focus on machines requiring long ranges and rapid refueling for continuous operation, while increasingly stringent environmental regulations and carbon pricing provide strong incentives for the transition from fossil fuels to hydrogen or hybrid solutions. Together, these factors outline a realistic pathway for hydrogen integration in mining over the next decade, establishing a foundation for broader adoption in the longer term.

8. Conclusion

As one of the most energy-intensive industries, the mining sector is at a critical point in the global transition to sustainable energy. Hydrogen has emerged as a viable alternative to fossil fuels, capable of decarbonising critical mining operations from heavy-haul vehicles to on-site power generation. While current applications are still limited and face challenges such as infrastructure development, cost and safety, ongoing pilot projects and technological innovations are paving the way for wider adoption. Case studies and global initiatives show a growing interest and investment in hydrogen-powered solutions, especially in regions with supportive policy frameworks and abundant renewable resources.

This review highlights hydrogen's versatility across production, transportation, and storage systems. The optimal approach whether on-site or off-site production depends on energy availability, infrastructure, and economic feasibility. Hydrogen production pathways, categorized by color codes, vary in carbon footprint. Green hydrogen, produced via electrolysis with renewable energy, is ideal for sustainable mining. In contrast, hydrogen from fossil fuels, i.e. grey, brown, black, has high CO_2 emissions. Low-emission options, i.e. blue, turquoise, yellow and pink, use different energy sources. Transportation options, including compressed gas, liquid hydrogen, and liquid organic hydrogen carriers, must carefully consider energy density, safety, and logistics. Storage solutions must be tailored to operational requirements, especially when integrated with intermittent renewable energy sources. Given the unique geographical and operational challenges of mining sites, successful hydrogen deployment requires customized, location-specific strategies.

Energy system modeling supports the integration of hydrogen into hybrid renewable energy systems and shows environmental and economic benefits, especially for off-grid and remote mining operations. Nevertheless, key challenges persist, including the premium cost of hydrogen technologies, insufficient infrastructure scalability, and lagging regulatory frameworks that hinder widespread adoption.

The adoption of hydrogen technologies represents a transformative opportunity for the mining sector to achieve decarbonisation while enhancing operational efficiency. Leading companies are investing in hydrogen-based applications such as on-site hydrogen production, hydrogen-powered fuel cell vehicles for mining and even green metallurgy. The article presents examples of hydrogen-powered trucks and excavators for the mining industry. Some of these demonstration vehicles have already reached a higher technological maturity, which proves their suitability for real-world operation. Notably, hydrogen-powered long-haul trucks, already available in the market, show promise for greening mining logistics operations.

However, ensuring safety in this transition process remains a complex but important undertaking. The combination of mining-specific hazards and the properties of hydrogen requires a multi-layered approach to risk management. This includes advanced detection technologies, robust infrastructure, workforce training and regulatory oversight. Lessons learned from previous incidents highlight the importance of proactive safety planning, while newer innovations such as hydrogen sensors and improved ventilation systems offer promising ways to mitigate risk.

Realizing hydrogen's full potential in mining will depend on three key factors: mature technologies, strategic deployment frameworks, and unprecedented cross-sector collaboration. Industry leaders, researchers, and policymakers must unite to address technical barriers, economic constraints, and policy gaps – developing scalable solutions tailored to diverse operational contexts. By achieving this synergy, hydrogen can transform mining into a cleaner, safer, and more efficient industry while establishing it as a driving force in the global transition to sustainable resource development.

CRediT authorship contribution statement

Nina Lokar: Conceptualisation, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review and editing. Miguel Muñoz Ortiz: Investigation, Methodology, Visualization, Writing – original draft. Amira Rachah: Conceptualisation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. Tazrin Ahmed: Investigation, Methodology, Visualization, Writing – original draft. Espen Vinge Fanavoll: Investigation, Methodology, Writing – original draft. Xiang Ma: Funding acquisition, Investigation, Methodology, Writing – original draft. Blaž Likozar: Conceptualisation, Funding acquisition, Supervision, Writing – review and editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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