International Labour Organization

ILO brief

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Powering the Future: Green Hydrogen and the Workforce of Tomorrow

Key points

- Green Hydrogen (GH2) is emerging as a vital solution for decarbonizing hard-to-abate sectors, including steel, cement, aviation and shipping. Beyond its potential contribution to environmental sustainability, GH2 presents opportunities for economic growth, energy security and job creation – particularly for countries rich in renewable resources. However, the GH2 sector faces challenges as it is a nascent technology with high costs, uncertain demand, infrastructure gaps and competition from other energy technologies. Thus, a successful transition to incorporating GH2 energy will rely on agile and inclusive skills ecosystems that balance supply and demand.
- While few entirely new occupations are expected to emerge as the sector develops, large-scale reskilling and upskilling are essential for creating a workforce whose skills align with market needs. The skills that workers will need span the full GH2 supply chain, including research and development (R&D), infrastructure to production frameworks, conversion (power-to-X), storage and distribution. Countries intending to develop their GH2 capacities must also address the skills gaps of workers in their policies, economic planning, and safety and regulatory compliance mandates. This includes skills gaps in the public sector. For example, case studies from Australia, Chile and the United Kingdom have demonstrated how comprehensive national strategies regarding the implementation of GH2 solutions can integrate vocational training, cross sector partnerships and regional workforce planning.
- Therefore, key recommendations of this brief include: developing national policies and GH2 strategies that give workers the skills they require early in their work training; expanding hydrogen-specific vocational education; and supporting collaboration between the GH2 industry and educational institutions. To achieve those goals, the following measures are required: including and supporting excluded groups; creating local jobs; upskilling teachers and trainers, providing hands-on training, and facilitating the rapid adoption of evolving technologies. In addition, responsive skills systems underpinned by data platforms that monitor workforce and technology trends and that enable training programmes to rapidly adapt to emerging trends will be required. The aforementioned recommendations make clear that a proactive approach focused on skills development is essential for unlocking the potential of Green Hydrogen and ensuring the future of clean energy.

1. Introduction

The global GH2 sector is still in its initial stages of development, but it holds significant transformative potential. With the right policies and strategic planning, countries can develop this emerging market, thereby reducing greenhouse gas emissions and mitigating the impact of climate change. However, there is uncertainty about growth timelines, required skills, workforce needs and the specific occupations that will be required. In response, many countries are working to create more flexible skills systems and agile training programmes that have the flexibility to respond accordingly.
This policy brief explores the role that GH2 and its derivatives can play in the transition to low-carbon economies, especially in hard-to-abate sectors. The brief also explores the current state of the GH2 sector; uncertainties that are shaping the sector, the emerging skills landscape across industries and supply chains, and how national skills-development frameworks can adapt to support GH2 growth. It also offers global examples and practical recommendations for creating an enabling policy environment that can effectively harness the potential of GH2, including skills planning and infrastructure development.

1.1. GH2 as an emerging contributor to broader climate change efforts

Since the adoption of the Paris Agreement on climate change, many countries have committed to achieving net zero by 2050 with the aim of keeping average global temperature increases below 2° Celsius above pre-industrial levels (United Nations Framework Convention on Climate Change 2016). However, countries must have a structured approach to carbon abatement and prioritize both cost-effective and technically-feasible measures that will help them in achieving net zero.

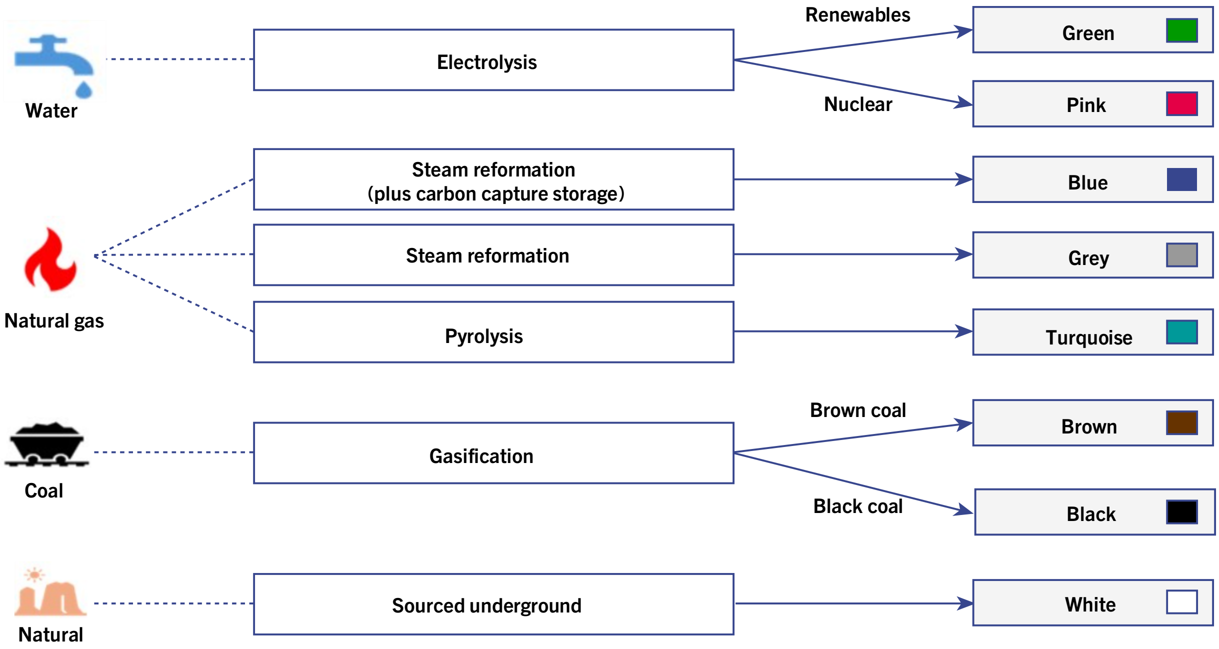
A commitment to carbon abatement prioritizes improving energy efficiency and reducing emissions. Those two elements are widely regarded as the most cost-effective measures available since they are not usually capital intensive and they lower overall energy consumption, which contributes to energy affordability and reduces the need for significant investments in new infrastructure or fuel supply chains. The International Energy Agency cites energy efficiency as the "first fuel", emphasizing that it is easily implemented and has the ability to reduce costs. Once energy efficiency measures are in place, an electrifying process that uses low-carbon sources, including renewables, becomes the next step in abatement. Within the carbon abatement process, Green Hydrogen is often only considered after other fuel efficiency measures have been attempted or when alternatives are not viable. Therefore, the widespread adoption of GH_2 may be delayed until more commercially mature and cost-effective solutions have already been explored (Motherway 2019). However, sectors such as steel and cement production, as well as shipping and aviation, are inherently difficult to electrify and therefore hard to decarbonize but are also significant contributors to global greenhouse gas emissions. Given this burden of emissions, those industries are more likely to adopt a GH_2 carbon abatement option (International Renewable Energy Agency (IRENA) 2021). This underscores the potential of GH_2 to support a net zero transition for certain industries that face unique challenges. Furthermore, the ability to store GH_2 is a valuable asset for enhancing energy security in the face of global supply uncertainties and its capacity to convert renewable energies means that the availability and distribution capacities of power generated by wind and solar is improved (World Economic Forum (WEF) 2023).

1.2. Using and generating Green Hydrogen

Hydrogen is currently used in many industries, including petroleum refinement, semiconductor manufacturing, rocket fuel for the steel industry, pharmaceutical products and fertilizer production. For example, ammonia production in the fertilizer industry uses 55 per cent of globally available hydrogen. Hydrogen can also be used as an input for fuel cells that produce electricity for vehicles or other machines or used in gas turbines (WHA International 2023). When considering the occupations and skills required for the production of GH2, it should be noted that hydrogen can be produced in a variety of ways, as shown in figure 1, and that the method of production influences the type and extent of skills required by the worker.

The differences in greenhouse gas emission rates by hydrogen production type is illustrated by the various colours. Black and brown indicate high CO_2 emissions, while turquoise and grey are medium, blue is low, and pink and green show minimal amounts (Global Energy Infrastructure 2021).

Figure 1. Hydrogen production: Types of processes



Source: Stanwell 2024.

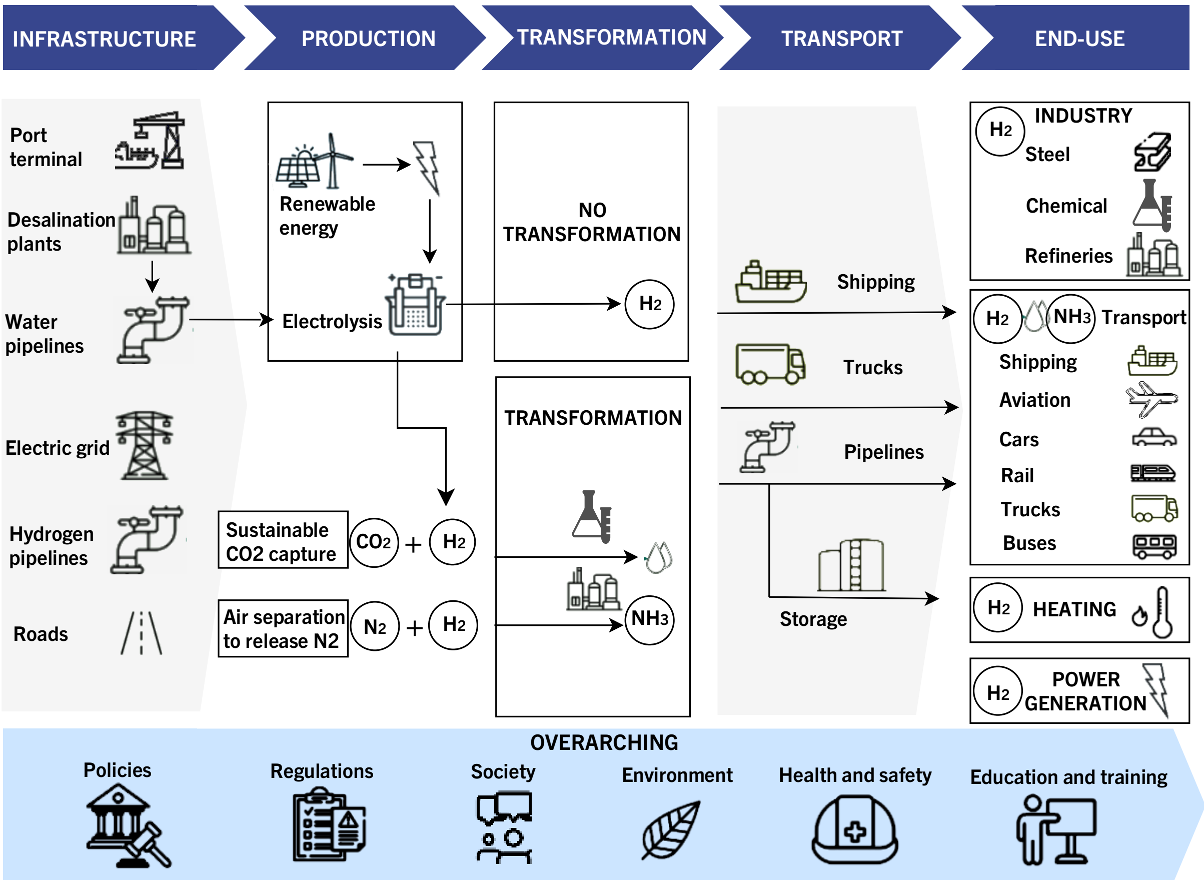
The implications for occupations and skills demand therefore varies depending on the type of hydrogen produced and its end use. For example, pink hydrogen projects require nuclear engineers, while green hydrogen projects depend on renewable energy specialists. If hydrogen is converted into synthetic fuels, such as kerosene, chemical engineers with expertise in processes such as Fischer-Tropsch synthesis will be essential. The current hydrogen market is primarily fossil-fuel based, but an area in which major growth is predicted is Green Hydrogen. Therefore, over time, jobs linked to fossil-fuel based hydrogen production may decline, while employment in renewable energy will likely grow and certain workers in the fossil fuel industry may be reskilled or upskilled so that they can work within the GH_2 supply chain. The size of the hydrogen market is expected to increase and this will affect the number of jobs available, with both short- and long-term employment opportunities for GH_2 workers. For example, the construction of ports, pipelines and storage capacities can provide temporary employment opportunities (United Nations Industrial Development Organization (UNIDO), IRENA and German Institute of Development and Sustainability (IDOS) 2023) while more sustainable job opportunities for more technical demanding job roles that require upskilling and reskilling development, will be needed in the production and electrolysis, mobility, storage and end-of-life phases of the GH_2 value chain.

1.3. Green Hydrogen offers value addition potential: Power-to-X (PtX)

Hydrogen can be converted into other molecules, using nitrogen and carbon sources, including carbon dioxide (CO2). The process of converting electricity from renewable sources into other products is referred to as Power-to-X or PtX. This conversion facilitates the storage, transportation and use of hydrogen needed in the production of various chemicals, fuels and materials (Schreiner et al. 2024). The CO2 can be captured from the air in industrial processes or from renewable biological sources. In order for the process to be considered green, it must use renewable electricity and CO2 from direct air capture or a renewable biological source. That process is referred to as de-fossilization, since carbon is still utilized but is not sourced from fossil fuels (International PtX Hub n.d.). Some of the fuels that can be synthesized through various chemical processes include methanol, diesel, methane and kerosene. When combined with nitrogen, hydrogen can be converted into ammonia and its derivatives, including ammonium nitrate, which is used in fertilizer production (GIZ 2020). Figure 2 outlines various PtX pathways.

Since the electrolysis process used to generate Green Hydrogen from renewable energy sources consumes large volumes of clean water, scaling up GH2 production requires significant amounts of water. That requirement may raise concerns within communities since many areas with strong solar and wind potential are water scarce. In those cases, seawater desalination is a possible solution. The desalination process not only supports hydrogen production but can improve water access for local communities and industries. The process of desalination is widely used globally, with over 16,800 plants supplying fresh water to around 300 million people in 150 countries (Eke et al. 2020). However, it is not without its challenges. Desalination is energy intensive and improper management of its by-products, particularly brine, can be harmful to the environment. In addition, the amount of energy required depends on factors such as water quality, treatment level, the technology used and plant capacity.

Figure 2. Green Hydrogen and the PtX supply chain



Source: Ndadi and Reihle 2023.

Figure 2 illustrates how PtX is central to the development of GH_2. It not only involves various processes, technologies, energy systems and sectors, (Schreiner et al. 2024) but also has a significant influence on the skills required by workers involved. Research indicates that between 50 and 200 different job roles could be created in the PtX supply chain (International PtX Hub 2024). Factors such as the size of the local market, and the policies and regulations adopted by specific countries will affect the number of temporary and permanent jobs created within different regional contexts (International PtX Hub 2024). The advancement of GH_2, PtX and the creation of new jobs mean that workers in the sector will require new skills in some cases, or reskilling and upskilling in other instances. To ensure that opportunities for job creation and fulfilment are optimized, a coordinated approach across the policy, industry and education and training spectrum will be required. However, equitable and inclusive large-scale GH_2 deployment is likely to encounter significant challenges in the area of workers' skills and in terms of the production and use of GH_2.

▶ 2. Challenges impeding GH2 scale-up

Before full commercialization of GH2 production can occur, several significant challenges must be addressed. Those challenges include the status of GH2 as a nascent technology with high production and transportation costs, limited electrolyser manufacturing capacities and uncertainty surrounding project development timelines. In addition, GH2-related policy remains unclear in many countries, which increases the investment risk. Meanwhile, GH2 must compete with other low-carbon technologies that are currently more cost effective or mature, further complicating scale-up and impeding market penetration.

2.1. A nascent market with cost barriers

The GH_2 market is in a phase of evolution and thus the anticipated timeframe for achieving commercial viability is unclear. Estimates by IRENA indicate that an 80 per cent reduction in costs across the production life cycle will be needed to reach commercial viability (IRENA 2020b). Advancements in production technology, infrastructure development and technology learning will be needed to reduce costs, but the timelines for those advancements are difficult to predict. Likewise, a well-trained R&D workforce and streamlined operations can cut costs by improving efficiency, reducing down time and accelerating innovation.

A substantial portion of the demand for GH_2 is anticipated to be in major consumption markets, including Europe, Japan, China and the United States of America (Plug 2024). GH_2 pricing from potential supply markets, such as Australia, Chile, Morocco, Namibia and South Africa, must take into consideration infrastructure costs related to transportation, distribution and storage (Shafiee and Schrag 2024). Transport and storage requirements for GH_2 vary significantly based on distance to market and the form in which hydrogen is transported or stored. In some cases, high transport and storage costs can render GH_2 commercially unfeasible (Yang et al. 2023). Transport logistics are also highly dependent on hydrogen-compatible infrastructure, which includes components such as cryogenic tankers and hydrogen pipelines and requires highly trained and specialized engineers and maintenance specialists. Commercial GH_2 projects also require logistics experts, engineers and infrastructure planners who understand GH_2-specifics. Those jobs are not entirely new but are the evolution of established roles that have evolved in response to the needs of the GH_2 sector.

2.2. Slow scale-up

In 2023, global electrolyser manufacturing capacity grew by over 25 per cent, with China accounting for half of that increase. However, to meet the demands of planned GH_2 projects, electrolyser production capacity may need to quadruple and the scaling up of GH_2 production moves slowly, creating potential bottlenecks that could hamper scale-up (IEA 2023). Scaling production requires not only technical experts but also equipment operators, project managers, site planners and logistics coordinators with GH_2–specific knowledge. In addition, given the newness of the market, additional infrastructure requirements such as new or upgraded ports, pipelines, desalination equipment and storage facilities may add billions of dollars to the cost. A further constraint to rapid scale-up of GH_2 technologies is uncertainty with regard to construction logistics, as is often the case with new technologies and large infrastructure projects. For example, even when projects are deemed commercially viable and reach a final investment decision, building megaprojects can be plagued by cost and time overruns (Crompton and Young 2022). Those obstacles must be identified from the beginning of a project and country-level strategies must be implemented to enable quick scale up.

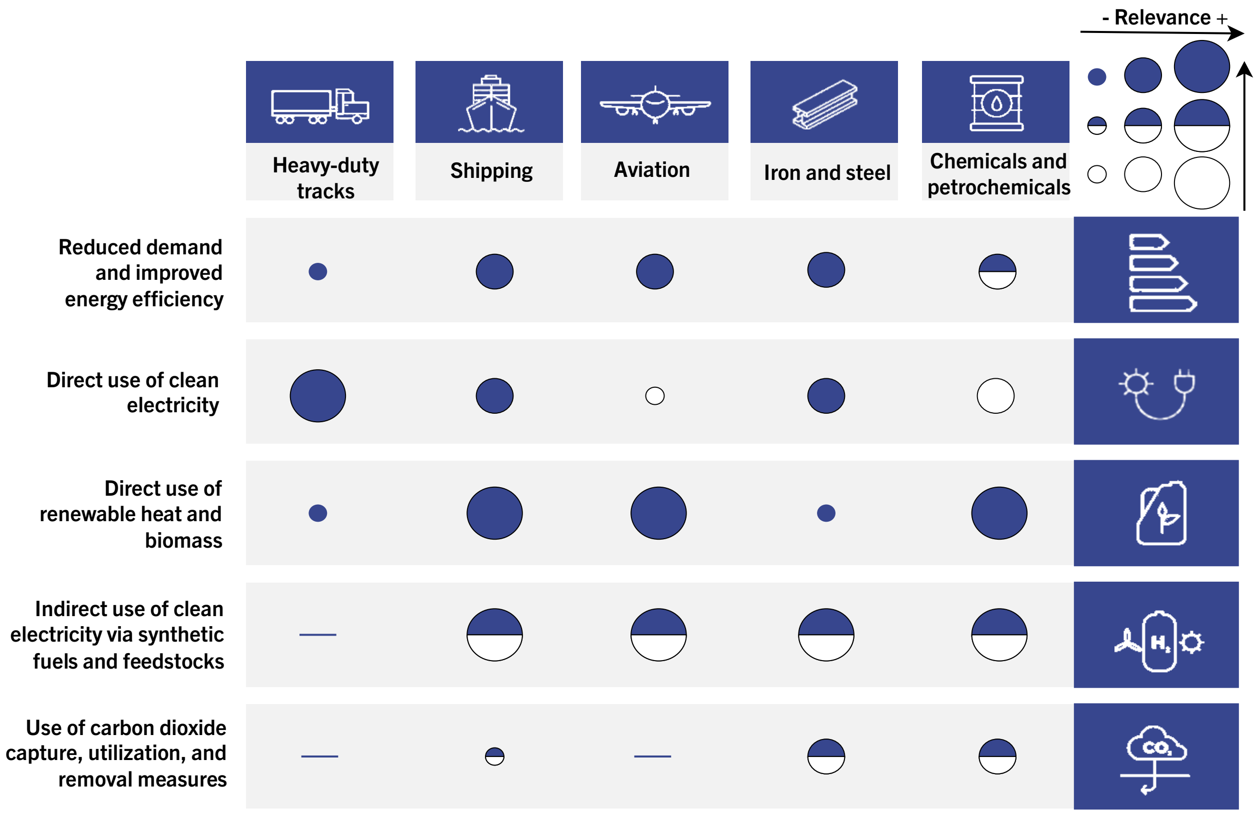
2.3. Uncertain policy environment

GH_2 has the potential to be a competitive solution for meeting net zero emissions by 2050 in hard-to-abate sectors. The time to commercial viability may depend on the rates of carbon taxes levied on other carbon-intensive fuels or on the types of regulation associated with carbon life cycle emissions, including cap-and-trade schemes and carbon budgets (Ueckerdt et al. 2024). Those policy instruments effectively serve as a subsidy for GH_2 and other low-carbon options, and it has been estimated that between US$2 trillion and US$4 trillion will be needed to meet current policy objectives for net zero by 2050 per the Paris Agreement (Palladino 2024). Given differences in policy, the amount will vary by country and a cost abatement analysis will need to be carried out to determine which sectors can sustain GH_2 commercial viability (Bloomberg 2024; Chugh and Taibi 2021; World Bank 2023). IRENA states that “An integrated policy approach is needed to overcome the initial resistance and reach a minimum threshold for market penetration, resting on four central pillars: building national hydrogen strategies, identifying policy priorities, establishing a governance system and enabling policies, and creating a system for the guarantee of origin for green hydrogen" (IRENA 2020a). Policies will vary depending on the maturity of the technology and the progress of GH_2 projects, as well as where in the supply chain the policy is applied. While comprehensive policies are essential, successful implementation of those policies will, moreover, depend on civil servants with appropriate skill sets who can develop regulations, issue permits and assess environmental impacts. Indeed, a frequently overlooked skills gap exists within the public sector itself, where limited technical capacity can delay policy implementation and undermine investor confidence.

2.4. Competing technologies and workforce readiness

Other technologies, such as electrothermal batteries and heat pumps, are competing with GH_2 in certain sectors and can be more broadly applied across sectors. In hard-to-abate sectors, factors such as energy efficiency, direct electrification, biofuels and carbon capture and storage (CCS), which can allow for the continued use of fossil fuels, contribute to making other technologies more attractive than GH_2 (IRENA 2024a). Many market analysts are therefore revising GH_2 demand predictions downward compared with earlier estimates (Deconinck 2024). Figure 3 illustrates the options available in various economic sectors and their relevance to GH_2 and PtX markets. The figure shows that cost is a critical factor in determining the energy choices made within a sector.

Figure 1. Options for decarbonizing hard-to-abate sectors



Source: Deconinck 2024.

Beyond technological competition, GH_2 adoption also depends on workforce readiness. While cost and maturity influence technology choices, the availability of skilled professionals is equally critical for successful deployment.

As competing technologies and GH_2 mature, the latter must determine its value proposition and demonstrate that it is not just technologically promising, but that the skills of the workforce can support its adoption. At present, educational and worker programmes to build GH_2 skills are inadequate. If the hydrogen industry experiences rapid growth, this slow response could lead to reactive skills development where efforts to train and upskill the workforce lag behind market needs. This can create bottlenecks in project implementation and increase transition costs. There is currently a critical shortage of qualified professionals capable of designing, deploying, and maintaining hydrogen systems. Additionally, there is a lack of expertise required to develop technical standards, design strategic and regulatory frameworks and manage complex project cycles (IRENA 2024b). Without timely investments in skills and training, that talent gap could significantly hinder the adoption of hydrogen technologies and make the energy transition more costly and inefficient for countries and industries.

▶ 3. To meet growing demand, an effective GH2 skills ecosystem is required

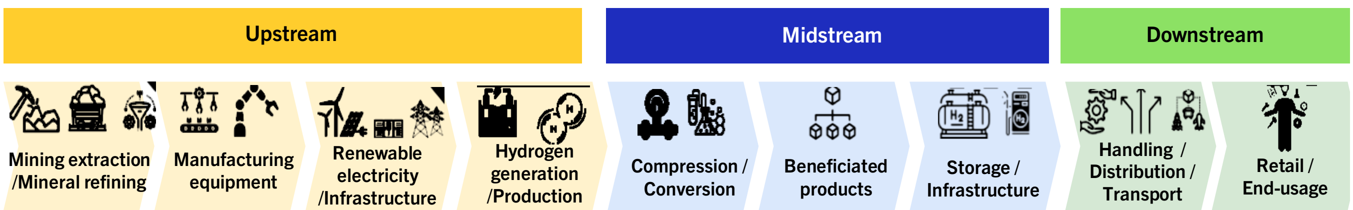
Effective national GH2 skills strategies require local planning and the creation of "skills ecosystems" that engage government, industry and education and training stakeholders along the entire supply chain. Without the alignment of industry, education and training, there is a risk that students will graduate with skills that are misaligned with industry needs. Continuous feedback loops between employers on the one hand and educators and trainers on the other are therefore essential. A truly effective GH2 skills ecosystem must also train workers employed in supporting roles required across the supply chain, including in climate science, finance, procurement, regulatory compliance and social and environmental impact assessment. Those areas are often overlooked but are critical in avoiding implementation bottlenecks and ensuring the success of projects. Similarly, the skills required for designing and building an enabling infrastructure must be addressed in national planning efforts.

Since the GH2 skills landscape is in its early stages, with great potential for transformation, there are significant opportunities for governments and businesses to strategize and develop proactive supportive policies. Developing such policies early on in GH2 development will ensure that all relevant stakeholders are involved and an effective ecosystem is created. Research indicates that countries that invest in young people, women and vulnerable groups within society see stronger local participation and reduced regional inequality across their workforces (AEP 2024; FTI Consulting 2020; Ministry of Skill Development and Entrepreneurship 2015). Comprehensive policies will also support an agile response to hydrogen demand in anticipation of the scaling up of the skills required and will ensure flexibility as the GH2 sector matures and its workforce evolves. Social dialogue, involving governments and employers' and workers' organizations, helps anticipate skills needs, co-design training programmes and build broad support for skills reforms as the sector scales.

▶ 4. Occupations and skills demand: Who is needed to build the GH_2 economy?

To analyse skills demand in the GH2 industry for the purposes of this brief, a value chain approach was used, as shown in figure 4. The approach was applied to the three main segments of the GH2 value chain: upstream (hydrogen production), midstream (hydrogen transport and storage infrastructure; often the most labour-intensive segment) and downstream (demand sectors).

Figure 2. Green hydrogen project and market value chain



Source: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2024.

The analysis first mapped the upstream, midstream and downstream activities of the value chain. That step was followed by the identification of occupations, skills and qualifications required at each stage of the value chain. Data was gathered from a range of sources and a structured process was applied, beginning with a review of existing literature to identify key occupations and related skills and qualifications. That process was complemented by an analysis of national and international reports, country-specific strategies and roadmaps, policy documents, academic publications and industry analyses. Finally, occupations, skills and qualifications that were repeatedly cited across multiple credible sources were mapped to ensure consistency and relevance.

4.1. Upstream: Inputs and production

The upstream segment of the GH2 value chain consists of production processes: mineral mining, extraction and refining; manufacturing of equipment; renewable electricity generation and associated infrastructure; and hydrogen production and generation (DNA Economics 2023). Key activities within that segment include R&D, planning and support functions, manufacturing of electrolysers, construction and operation of renewable energy plants to supply green electricity, and the construction of GH2 plants and electrolysis systems.

4.1.1. R&D, planning and support

Given the nascent nature of the GH2 sector, the occupations in demand in the upstream segment require high-level skills and include: research scientists, design engineers, hydrogen economists and finance managers (see table 1). Some of those occupations may also be in demand during the pre-feasibility and feasibility stages of a GH2 project. Planning and innovation, as well as developing policy and business cases, are critical in the upstream segment.

▶ **Table 1. Occupations and skills required in R&D, planning and support**

Commonly identified occupations

- Research scientists: Drive innovation in hydrogen production, storage and utilization. Are skilled in climate and greenhouse gas analysis and environmental and social sustainability assessments.
- Design engineers: Develop and refine new technologies to improve performance and commercial viability. Are skilled in technology innovation, systems design and environmental impact evaluation.
- Environmental and regulatory compliance specialists: Ensure compliance with environmental laws and promote public trust. Offer expertise in policy and regulatory frameworks and environmental risk analysis.
- Hydrogen economist and policy analysts: Analyse market trends, model business cases and shape GH_2 policy. Are skilled in economic risk assessment, market research and policy development.
- Finance managers: Develop investment strategies and secure funding for hydrogen projects. Offer expertise in investment and financial analysis.
- Human resource specialists and workforce advisors: Support organizational and sectoral workforce planning by identifying training needs, advising on talent strategies and contributing to the design of training and education programmes tailored to the evolving hydrogen economy.

Sources: Cogent Skills 2024; DHET 2024; EU 2023; EU 2022; EWSETA 2023; GIZ 2024; Government of India 2024; Hydrogen Skills Alliance 2022; IDRIC 2022; Midlands Engine 2024; International PtX Hub n.d.; Government of Queensland 2022; Wits REAL 2024.

4.1.2. Manufacturing, construction and electrolysis

Occupations required for the stages of manufacturing, construction and electrolysis are presented in table 2. Certain low- and medium-skilled occupations, such as welders and plant operators are included, although the majority of occupations require high-level skills. Most of the occupations required for this stage already exist in the current labour market, but a more expanded set of specialized skills are needed in the hydrogen sector. For example, specialized skills are needed for the construction and operation of renewable energy plants that supply green electricity, but many of the skills needed for that work can be leveraged from a relatively mature current workforce, due to the steady growth of the renewables sector in recent decades. The sector employed 16.2 million people in 2023, an increase from 7.3 million in 2012 (IRENA and ILO 2024). An extensive list of skills associated with renewables are not covered in this brief, but it should be noted that the number of workers with renewable energy skills will have to increase as the number of GH2 plants grows and commercial viability increases. Therefore, a skills deficit is expected based on current numbers of workers with those skill sets. To meet the specific demands of the green hydrogen sector, targeted upskilling or reskilling of workers will be necessary.

For the physical construction of GH2 plants, hydrogen infrastructure construction could utilize worker skills already available from other renewable energy and chemical processing sectors, including the gas industry. Some workers involved in manufacturing components for hydrogen plants will likely need additional training to keep pace with new technologies associated with green hydrogen infrastructure (DTIC 2023). The demand for manufacturing of hydrogen equipment such as electrolysers and fuel cells in a specific region or country will depend on how much manufacturing capacity already exists in those locations and how much of the production can be done locally. For example, in the light of large infrastructure initiatives currently in progress around the world, concerns have been raised regarding the lack of workers with specialized skills in fabrication and welding and the ability of the industry to complete projects accordingly (Energy Institute 2023).

Electrolysis and desalination are critical processes in the production of green hydrogen, particularly in water-scarce regions. Desalination plants, which provide the purified water needed for electrolysis, require water treatment experts, mechanical and chemical engineers, instrumentation and electrical technicians and environmental specialists. Electrolysis, which involves splitting water into hydrogen and oxygen using electricity from renewable sources, relies on expertise across multiple fields, including electrical systems, chemistry, electrochemistry and energy conversion technologies. (France Hydrogène 2022).

▶ **Table 2. Occupations and skills required in manufacturing, construction and electrolysis**

Commonly identified occupations

- Boilermakers and welders: Weld different types of materials. Some are specialized in high temperature, high pressure and chemical environments.
- Plant operators: Operate and maintain machinery used in hydrogen equipment manufacturing and hydrogen production systems.
- Electrolysis technicians: Responsible for the operation, maintenance and repair of electrolysers to ensure the reliability and efficiency of hydrogen production systems.
- Health and safety officers: Ensure compliance with occupational health and safety regulations, oversee workplace safety and risk management, reporting and safety system management.
- Engineers (industrial chemical, mechanical, electrical, etc.): Lead the design, prototyping, integration and optimization of hydrogen systems and components.
- Quality assurance experts/inspectors: Perform quality assurance inspection throughout the hydrogen equipment manufacturing, construction and production process.
- Heating, ventilation and air-conditioning (HVAC) technicians: Install and maintain heating, ventilation and cooling systems.
- Environmental and regulatory compliance specialists: Ensure adherence to environmental laws and promote public trust.
- Finance managers: Manage budgets, operation costs, capex expenditure, revenue and debt burdens.
- Water treatment experts: Manage the purification processes needed to produce high-quality water for electrolysis.
- Instrumentation and electrical technicians: Install, maintain and calibrate the instruments and electrical systems used to monitor and control plant operations.

Sources: Cogent Skills 2024; DHET 2024; EU 2023; EU 2022; EWSETA 2023; GIZ 2024; Government of India 2024; Hydrogen Skills Alliance 2022; IDRIC 2022; Midlands Engine 2024; International PtX Hub n.d.; Government of Queensland 2022; Wits REAL 2024.

4.2. Midstream: Processing, storage and transportation

The midstream segment of the GH2 value chain involves compression/conversion, the production and processing of beneficiated (value-added) products and storage and transportation (DNA Economics 2023). For this segment, various specialized occupations are required to handle the processing, storage and transportation of GH2, including environmental and regulatory compliance specialists, industrial process engineers, research scientists and electrical, mechanical and chemical engineers, as outlined in table 3. Depending on whether the hydrogen is used and transported directly or converted into a different product, chemical engineers specializing in compression and conversion, using the Fischer-Tropsch process for example, are needed for synthetic kerosene production. While there is some overlap with the skills required of workers operating in gas and other forms of hydrogen production, practical experience with operating and maintaining GH2 and PtX plants remains a scarce skill set among workers. That indicates a gap between existing skill sets and the specialized expertise required for constructing and operating plants as well as the scale-up of GH2 infrastructure. Furthermore, analysis shows that it is in fact in the earlier stages of infrastructure development that pipelines, ports and other construction projects are needed to adapt to new supply chains and the handling of materials. Meeting infrastructure needs for GH2 and PtX products will require workforce upskilling.

▶ **Table 3. Occupations and skills required in the midstream segment of the GH2 value chain**

Commonly identified occupations

- Boilermakers and welders: Weld different types of materials. Some are specialized in high temperature, high pressure and chemical environments.
- Plant operators: Operate and maintain hydrogen compression and conversion equipment.
- Health and safety officers: Ensure compliance with occupational health and safety regulations, oversee workplace safety and risk management, reporting and safety system management.
- Engineers and technicians (industrial chemical, mechanical, electrical, etc.): Design, install, and maintain systems used in hydrogen compression, conversion, process and storage.
- Environmental and regulatory compliance specialists: Ensure adherence to environmental laws and promote public trust.
- Finance managers: Manage budgets, operation costs, capex expenditure, revenue and debt burdens.
- Hydrogen storage experts: Develop and manage cryogenic or pressurized hydrogen storage.
- Industrial process engineers: Integrate hydrogen into manufacturing processes.
- Research scientists: Conduct R&D to improve hydrogen production, fuel synthesis and storage technologies.
- Quality assurance experts/inspectors: Perform quality assurance inspections during the processing, storage and transportation of hydrogen.
- Heating, ventilation and air-conditioning (HVAC) technicians: Install and maintain heating, ventilation and cooling systems.
- Market analysts: Conduct market research for GH2 and PtX products.

Sources: Cogent Skills 2024; DHET 2024; EU 2023; EU 2022; EWSETA 2023; GIZ 2024 Government of India 2024; Hydrogen Skills Alliance 2022; IDRIC 2022; Midlands Engine 2024; International PtX Hub n.d.; Government of Queensland 2022; Wits REAL 2024.

4.3. Downstream: Utilization and end-use

Key activities in the downstream segment include the handling and distribution, transport and retail or end usage (DNA Economics 2023). The segment is focused on the final application of green hydrogen across sectors and contributes directly to achieving decarbonization goals and creating value within a country's economy. Major industries involved in the downstream segment include steelmaking, oil refining, fertilizer production (ammonia and other chemicals), and power generation through the production of fuel cells, which are either used in combination with natural gas or used in gas turbines or in mobility applications such as hydrogen-powered trucks, buses, trains, ships and aircraft.

An essential part of the downstream segment is end-of-life management, which encompasses decommissioning, dismantling, recycling and repurposing equipment (such as fuel cells, electrolysers, tanks and vehicles). Occupations and skills that are required in the segment are listed in table 4. materials-handling technicians, chemists, fuel cell engineers, and GH2 compliance auditors. Upskilling will be a key feature of programmes to train workers for occupations in the downstream portion of the value chain. The reason for this need is that while there are workers who already have some of those skills, they will require training in specific chemical product transportation and safety considerations as well as in recycling and materials recovery. Given the newness of the GH2 market and the lack of practical experience of a large portion of the existing workforce, developing the skills of those working in the downstream segment will take time.

Table 4. Occupations and skills required in the downstream segment of the GH2 value chain

Commonly identified occupations

- Specialized truck drivers: Transport hazardous goods and have specific training in heavy-duty trucks
- Materials-handling technicians: Oversee the safe and secure movement of PtX products.
- Quality control officers: Ensure compliance with quality standards.
- Chemists: Develop and refine processes that convert GH2 into value-add products such as ammonia and methanol. Ensure product safety and environmental sustainability.
- Fuel cell engineers: Design, develop and optimize fuel cell systems for hydrogen-powered applications.
- Hydrogen economists: Analyse hydrogen market trends and pricing.
- Policy analysts: Draft GH2 strategies and regulations that enable the adoption and integration of green hydrogen into end-use applications.
- Hydrogen health and safety specialists: Create safety protocols for GH2 handling, distribution and transport.
- Environmental and regulatory officers: Ensure legal and environmental, social and governance (ESG) compliance.
- GH2 compliance auditors: Monitor and report on compliance with regulations, standards and protocols.
- Market analysts: Monitor hydrogen demand, consumer adoption patterns, and price trends to inform business decisions.
- Recycling and material recovery technicians: Provide specialized input to facilitate the recycling and recovery of metals and components from hydrogen technologies.

Sources: Cogent Skills 2024; DHET 2024; EU 2023; EU 2022; EWSETA 2023; GIZ 2024; Government of India 2024; Hydrogen Skills Alliance 2022; IDRIC 2022; Midlands Engine 2024; International PtX Hub n.d.; Government of Queensland 2022; Wits REAL 2024.

5. Skills supply: What are the key challenges impeding the GH2 skills supply?

Effective skills development is central to the successful growth and deployment of GH2 and PtX technologies. The sector demands a multidisciplinary workforce with skills across the areas of renewable energy, electrochemistry, occupational safety, systems integration and chemical engineering. As global investment in GH2 and PtX grows, so does the demand for technicians, engineers and operators skilled in electrolyser systems, fuel cells, hydrogen storage and downstream conversion processes.

The green hydrogen sector is still in development, meaning that technologies are evolving, project timelines are shifting and national strategies are still being formulated. Consequently, education and skills providers are contending with a shifting landscape and with many of the challenges identified in this brief. Since the commercial viability of green hydrogen could be years away in some parts of the world, demand for the training and employment of personnel with the skills required for GH2 production is a moving target. Specific skills and occupations required vary from country to country depending on national hydrogen strategies, the technologies available and industrial requirements. However, there is still common occupations and relevant skills required regardless of individual country circumstances. Those skills are often already used in other economic sectors, including renewables, and the chemical and infrastructure sectors because the skills required in the GH2 sector are similar to those already used by numerous engineers, technicians, welders and occupational safety experts. The result is competition for the same pool of workers with a given skillset. Training providers therefore need to conduct a broad-based assessment of the demand for skills training across traditional disciplines. Finally, the type of hydrogen being produced (green, pink, blue) and its end use (power, ammonia, shipping) has an impact on the skill set required and therefore training providers must ensure the provision of appropriate training.

Since the GH2 sector does not require a vast array of entirely new occupations, the challenge of developing the skills of workers is not due to the lack of skills but rather due to limited practical experience, particularly while global GH2 projects that are operational remain limited in number (European Union 2023). Therefore, significant reskilling and upskilling within existing job roles is required. Education and training institutions must be prepared to scale up delivery in key technical areas and to incorporate hydrogen-related competencies into current curricula, ensuring a strong emphasis on hands-on, practical training. In addition, technical and vocational education and training (TVET) systems must rapidly adapt to meet the evolving demands of the GH2 sector. Action taken to that end should include developing accredited, hydrogen-specific qualifications, embedding work-based learning and fostering stronger partnerships between industry and TVET providers so that curricula remains relevant and students and trainees can acquire practical market-relevant experience. The training being offered should, moreover, incorporate PtX technologies, which require expertise in chemical processing, automation, quality control and carbon life cycle assessment. To date, Australia and Germany have recognized the aforementioned needs and have incorporated hydrogen skills planning into their national energy and workforce strategies to decrease the likelihood of project bottlenecks, ensure inclusive economic participation and prepare an adequate number of skilled workers for the GH2 industry (IRENA 2020a).

Therefore, to adequately respond to shifting market demands, governments and educational and training institutions must coordinate their activities and proactively update curricula, while also scaling up the provision of hands-on learning opportunities. That may include activities such as apprenticeships, internships and on-the-job training, with adjustments made in line with market and project requirements.

▶ 6. National hydrogen policies and skills initiative strategies

In the light of the current GH2 landscape, governments are actively mapping skills gaps and designing hydrogen workforce development strategies suited to their national contexts, with certain countries focusing on skills as a critical part of their national strategies. Australia, Chile and the United Kingdom, for example, have successfully demonstrated how skills can be embedded into national hydrogen strategies, as depicted in table 5. Efforts to that end by the aforementioned countries provide a useful examples model for skills development for a just transition that can guide efforts by other countries to develop their GH2 sectors.

▶ **Table 2. GH_2 national skills development strategies: Skills initiatives and insights**

Country	Strategy overview	Key skills development objectives	Insights for skills development
Australia	National Hydrogen Strategy (2024) outlines a vision for the development of the country's GH_2 sector. Australian states and territories have adopted jurisdiction-specific measures and strategies, e.g., Queensland Hydrogen Industry Workforce Development Roadmap (2022–2032); Victorian Hydrogen Hub (VH2) – Hydrogen Skills Roadmap; Victorian Renewable Hydrogen Worker Training Centre	• Focus on TVET with accredited, hydrogen-specific skills courses. • Create strong industry-education partnerships to co-develop curricula and facilitate workplace training. • Support workforce development initiatives based on skills needs analysis and industry intelligence and guidance.	• Align training with real industry needs through co-design and placements. • Develop regional skills strategies to support local hydrogen hubs. • Utilize data insights to plan for hydrogen sector workforce needs.
Chile	National Green Hydrogen Strategy (2020) prioritizes workforce capacity-building for GH_2 leadership.	• Develop a local workforce of technicians and specialists with skills and knowledge to support a national hydrogen ecosystem. • Collaborate across government, industry, academia and technical centres to identify skills gaps in the GH2 value chain. Take timely action to build national GH2 capabilities.	• Invest in local workforce development in order to support the establishment of a national GH2 industry. • Enhance collaboration between the public and private sectors to promote early skills planning and implementation.
United Kingdom	UK hydrogen strategy (2021) aims to create 9,000 low-carbon hydrogen jobs by 2030 and 100,000 jobs by 2050.	• Invest in hubs like the Aberdeen-based Energy Transition Zone and Global Underwater Hub, to support the transition of workers from high-carbon to low-carbon industries through reskilling and upskilling programmes. • Develop energy skills forecasts, implement an energy apprenticeship scheme and create a skills accreditation framework e.g., for heat engineers employed in the hydrogen industry. • Provide incentives for project developers in order to promote the development of sector-relevant skills and contribute to quality job creation.	• Support a just transition by reskilling and upskilling affected workers, and leverage the hydrogen sector as a key opportunity for quality job creation. • Use relevant data to track the skills needed in the emerging GH2 sector and update strategies and programmes accordingly. • Identify and address barriers that limit private sector investment in skills development and the creation of decent work within the GH2 industry.

Sources: National Hydrogen Strategy, Australia (2024); National Green Hydrogen Strategy, Chile (2020); UK hydrogen strategy (2021).

A key insight from the review of national hydrogen policies and strategies is that effective green hydrogen skills development depends on localized planning and the establishment of comprehensive "skills ecosystems" across the GH_2 value chain that bring together national government, local authorities, trade unions, industry stakeholders and education and training providers. That coordination requires the joint collection of data and insights on short- and long-term skills supply and demand, particularly from the hydrogen industry. The data must then be used to design education and training programmes that deliver timely, location-specific and industry-relevant skills. Targeted investment and inclusive policies are also necessary to avoid workforce imbalances and to empower countries aiming to become major green hydrogen producers to drive innovation and equitable growth. At the same time, the expansion of the GH_2 sector presents an opportunity to facilitate the transition of workers from high-carbon to low-carbon industries through reskilling and upskilling efforts.

▶ 7. Conclusions and recommendations

The GH2 sector is still in the early stages of its development and faces competition from other emerging technologies. In addition, uncertainty remains regarding potential market size, demand growth, commercial viability and the timing and scale of skills needed. Building a successful GH2 economy will require an agile, inclusive skills system, one that holistically supports workers from the classroom to the control room. While only a few new occupations are expected to emerge as the sector develops, there will be a significant need to reskill and upskill the existing workforce for GH2-related roles. To support the emergence of a robust GH2 economy, this brief recommends the following measures to support an agile and robust skills ecosystem.

- **Create an enabling policy environment**

An enabling policy environment lays the foundation for a sustainable transition to GH_2 by providing regulatory clarity and enabling multi-stakeholder engagement and enhanced investment and can be achieved by creating and leveraging context-specific national roadmaps and implementation plans. Elements that contribute to this include: embedding skills planning into national hydrogen strategies from the outset; guiding workforce strategies, investment decisions and education and training priorities; encouraging localization and economic growth to promote domestic capacity in GH_2 production, storage and derivative manufacturing; setting clear milestones to support local industries and job creation; and establishing incentives such as tax breaks or grants for businesses investing in hydrogen skills development.

- **Build partnerships across sectors**

Countries must align hydrogen skills development with broader green energy and economic policies, including digital skills programmes and just transition initiatives, and must ensure that skills planning is an integral aspect of technology and industrial planning. Those actions will contribute to coordinated, context-specific government and industry partnerships and ensure the design and delivery of relevant training. Institutionalized social dialogue can strengthen these partnerships and ensure that skills interventions are relevant to the industry needs, support decent work and thus promote a just transition.

- **Deliver practical, inclusive training**

Training across all educational levels and for those already in the workforce must include not only upskilling and reskilling courses, but practical work experience. That objective can be achieved by expanding certified hydrogen training for those employed or intending to take up employment in certain professions and incentivizing businesses to provide hands-on experience, including in the form of apprenticeships and on-the-job training, as well as by working with business associations and professional certification bodies to design targeted worker training programmes. In addition, expanding and updating the curricula offered by vocational training institutions so as to deliver hydrogen-specific skill sets will support workers by providing them with up-to-date skills in line with current and anticipated labour market needs.

- **Support workforce development at the local level**

Although specific national contexts will drive overall GH_2 development, addressing location-specific issues will be critical for facilitating project implementation and creating long-term sustainability and social resilience. Actions that support local workforce skills development include the formulation of methodologies and tools to map skills needs by region and matching training with local context needs. Immediate steps should be taken to prepare the workforce for the transition to a GH_2 economy, including in areas where that transition has yet to begin, in order to facilitate a just transition and avoid scenarios in which local communities and workforces are left behind as the transition accelerates.

- **Spark interest and teach skills early**

In order to train workers in GH_2 skills early in their education, support in specific areas is needed. Actions that should be taken include: embedding hydrogen-linked competencies in Science, Technology, Engineering, and Mathematics (STEM) curricula, promoting vocational and tertiary education through demand-responsive curriculum development; ensuring that curricula reflect industry needs and emerging technologies through ongoing dialogue between educational institutions and employers.

- **Deliver a just transition**

Inclusivity should be made a priority, with the particular interests of young people, women, micro-, small and medium-sized enterprises and displaced fossil fuel workers integrated into GH_2 worker initiatives. Additionally, a process for communicating with and supporting those groups should be developed. Specific initiatives recommended here include: investing in design initiatives that actively engage young people, women and micro-, small and medium-sized enterprises; and providing targeted funding, mentorship and entrepreneurial training to increase participation in GH_2 value chains.

- **Monitor, adapt and scale up**

In order for the GH_2 sector to remain agile and responsive as the sector expands and evolves in the near and medium term, it is critical to establish a platform for collecting and collating real-time data on GH_2 projects and workers and to communicate the analysis on collected data to educational providers so that training systems can evolve in step with changing industry needs.

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