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INDUSTRIAL DEVELOPMENT ORGANIZATION

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International Renewable Energy Agency

IDOS

GREEN HYDROGEN FOR SUSTAINABLE INDUSTRIAL DEVELOPMENT

A POLICY TOOLKIT FOR DEVELOPING COUNTRIES

Acknowledgement

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First edition

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List of Abbreviations

ADB	Asian Development Bank
AHJ	Authorities having jurisdiction
BF-BOF	Blast furnace – basic oxygen furnace
BMBF	German Federal Ministry of Education and Research
BoP	Balance of plan
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CBDR	Common but Differentiated Responsibilities
CCS	Carbon capture and storage
CEM	Clean Energy Ministerial
CO_2	Carbon dioxide
CoC	Certificate of conformity
COP	Conference of Parties
CSR	Corporate social responsibility
DFI	Development finance institution
DRI	Direct reduced iron
EBRD	European Bank for Reconstruction and Development
ESMAP	The Energy Sector Management Assistance Program
EU	European Union
FDI	Foreign direct investment
GCA	Global Climate Alliance
GDP	Gross domestic product
GEP	Green Energy Park
GH2	Green hydrogen
GHG	Greenhouse gas
GHIC	Green hydrogen industrial clusters
GIZ	German Agency for International Cooperation

GPHI	Global Programme for Green Hydrogen in Industry
H_2	Hydrogen
H4D	Hydrogen for Development
IHEC	International Hydrogen Energy Center
HFC	Hydrogen and fuel cell
IAO	Implementation Authority Office
IEC	International Electrotechnical Commission
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
JETPS	Just Energy Transition Partnerships
Kg	Kilogramme
KPIs	Key performance indicators
LCOE	Levelized costs of energy
LCOH	Levelized costs of hydrogen
LCR	Local content requirement
LDC	Least developed country
LH2	Liquefied hydrogen
LOHC	Liquid organic hydrogen carriers
MDBs	Multilateral development banks
MENA	Middle East and North Africa
MoU	Memorandum of Understanding
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hour
NDCs	Nationally determined contributions
NGHRI	Namibia Green Hydrogen Research Institute

NH3	Ammonia
NHS	National hydrogen strategy
OECD	Organisation for Economic Co-operation and Development
O&M	Operations and maintenance
OPEX	Operations expenses
PEM	Proton exchange membrane
PGM	Platinum group metals
PPA	Power purchase agreement
PPP	Public-private partnership
PtX	Power-to-X
RAB	Regulated asset base
R&D	Research and development
RE	Renewable energy
SAF	Sustainable aviation fuel
SDGs	Sustainable Development Goals
SEZ	Special economic zone
SOEC	Solid oxide electrolyser cell
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USAID	United States Agency for International Development
VAT	Value added tax
VRE	Variable renewable energy
WACC	Weighted average cost of capital
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WTO	World Trade Organization


GH2

Foreword

Green Hydrogen represents a unique opportunity for the clean energy transition. Climate change is an existential threat to a sustainable future, but at the same time, facing up to the climate challenge is an opportunity to promote prosperity and a brighter future for all. Green hydrogen and its derivatives will play a vital role in the just energy transition.

This collaboration between UNIDO, the International Renewable Energy Agency (IRENA) and the German Institute of Development and Sustainability (IDOS) has synergized our collective commitment to fostering a global energy transition that leverages green hydrogen. This partnership focuses on amplifying international cooperation to facilitate the investment, policy-making and clean technology adoption, which are essential for inclusive and sustainable industrial development in line with the UN Sustainable Development Goals. All three organizations emphasize the transformative potential of green hydrogen, especially for developing countries with vast renewable energy resources, viewing it as a catalyst for low-carbon industrialization and job creation. However, the actualization of these economic benefits depend on factors like existing industrial capacity and accessibility to technology. Therefore, it is pivotal to have further benefit-sharing mechanisms in place to safeguard a just transition for the society as a whole.

We still have our work cut out for us in making the energy transition a reality. Currently, no mature green hydrogen market exists. However, the number of countries with national hydrogen roadmaps has more than tripled over the past two years, showing that many countries are readying themselves to start using green hydrogen and are planning how best to benefit from the economic opportunities it will provide. An essential prerequisite to the global scale up of green hydrogen is the development of the necessary policy and legal frameworks, and the coordination of international standards. Without regulatory clarity, green hydrogen projects are unable to move forward as they cannot plan or assess risk. This toolkit is the first to cover the entire green hydrogen value chain - including backward linkages, production and end-use - with a specific focus on developing countries. Developed under UNIDO's Global Programme for Hydrogen in Industry, which was launched in July 2021, it provides strategic guidance to maximize the local benefits of green hydrogen and includes concise policy sheets that outline the options to achieve this.

Going forward, this toolkit will serve as a valuable resource for developing countries that aim to embark on a pathway to industrialization fuelled by green hydrogen. It informs policymakers about the latest strategies, challenges and solutions for creating a local value chain around green hydrogen production. Based on these insights, country-specific needs may subsequently be addressed through further cooperation and projects.

By facilitating green hydrogen production in developing economies, UNIDO, IRENA and IDOS are propelling the clean energy revolution. We are supporting future industry leaders. We are caring for the workforce of tomorrow. We are striving for the just transition of industry: evolution from pollution to solution. We are working towards a sustainable future for all, driven by innovation.

Gerd Müller

Director General, UNIDO

Francesco La Camera

Director General, IRENA

Anna-Katharina Hornidge

Director, IDOS

Executive Summary

Green hydrogen (GH2) is gaining significant attention within the global energy landscape. As a clean and renewable energy carrier, GH2 holds the potential to transform a number of sectors, spanning heavy industries to shipping and aviation. Its benefits are far-reaching, ranging from the reduction of greenhouse gas emissions to reinforcing energy security and creating opportunities for green industrialization. However, to fully unlock GH2's potential, an equitable distribution of its benefits to all is indispensable. Against this background, the report "*GH2 for sustainable industrial development: A Policy Toolkit for Developing Countries*" reframes the prevailing narrative by shifting its focus away from the role of developing countries as producers and exporters in the future hydrogen market to highlighting the significance of the hydrogen value chain for developing countries themselves.

GH2: Unveiling opportunities and addressing challenges

GH2 possesses the potential to spark a transformation that drives industrial development and fosters innovation, with potentially beneficial impacts on all three dimensions of sustainability: economic (e.g. green industrialization, energy independence, increased participation in global trade and markets), environmental (e.g. accelerating decarbonization, in particular of hard-to-abate industries) and social (e.g. job creation, reliable energy access).

The toolkit identifies seven primary economic activity clusters within the GH2 value chain: in addition to the primary activities of (1) renewable energy generation and electrolysis, (2) conversion into Power-to-X (PtX), and (3) GH2 export, (4) local upstream manufacturing of electrolysers and renewable energy equipment can offer substantial impetus to the growth of the domestic GH2 industry. Similarly, (5) the decarbonization of domestic industries, (6) of transport, and (7) attracting foreign direct investment in energy-intensive industries represent opportunities to generate sustainable employment downstream, add long-term value and enhance international competitiveness.

Despite the potential for growth and cross-sectoral benefits in the GH2 industry, a number of multifaceted challenges need to be addressed. These include cost impediments, political instability, weak regulatory frameworks, bureaucratic hurdles, and the lack of off-take agreements. Additional challenges arise from uncertainties in international transport and concerns regarding the scale and dynamics of clean hydrogen trade, including the role of blue hydrogen as a transitional technology. Hence, to successfully scale up GH2 production in developing countries, adaptations across several dimensions will be necessary, including in infrastructure, regulatory frameworks, financial incentives and skills development. Concerted policy actions are imperative to harness opportunities and effectively navigate the many challenges. This report presents a comprehensive toolkit to guide strategic decision-making in this context.

Navigating a just transition: A policy mission for equitable change

The development of the GH2 value chain hinges on factors such as technological expertise, natural endowments, a supportive business environment, and past industrial development trajectories. Effective policy coordination plays a crucial role in laying the foundation for a robust localized GH2 value chain tailored to specific contextual factors. Policymakers must prioritize strategic interventions and instruments to achieve green industrial diversification, encouraging both existing and emerging industries to engage in the production of green goods and maximize the benefits of GH2 production. Such diversification has the potential to create more job opportunities and enhance the export potential of high-value green goods compared to only producing and exporting GH2. Countries that are unable to generate significant linkage effects should integrate GH2 trade with benefit-sharing mechanisms. This approach helps prevent the formation of export-driven energy enclaves within their borders and ensures a GH2 roll-out that is deeply embedded in and advocates for a just transition.

A 'clover approach' presented in the report outlines four key strategic considerations for the implementation of GH2 production: (1) prioritizing local use before export (*dual* approach); (2) aligning with a just transition and other national goals (*integrated* approach); (3) starting with smaller to medium-sized projects (*gradual* approach), and (4) sequentially implementing GH2 production and application (*phased* approach). By leveraging their comparative advantages and integrating GH2 into their overall vision and strategy, developing countries can promote sustainable development, technological advancement, and the creation of jobs.

In this context, the adoption of a comprehensive national hydrogen strategy focused on scaling up of domestic green hydrogen production through engagement in both upstream and downstream activities becomes a crucial step. This strategy provides clear policy direction for both project developers and investors. At the same time, it will only be effective when coupled with a robust regulatory framework to create a conducive environment for GH2 investment.

Fostering inclusive technology advancement and sustainable energy generation

Access to technology plays a pivotal role in the production of GH2, particularly given that core technologies such as solar PV cells, wind turbines, and electrolysers are predominantly manufactured in a few industrialized countries. One option is to implement local content requirements (LCRs) to bolster domestic manufacturing and leverage investments in long-term research and development to encourage local innovation and technology advancement. The caveat, however, is to prevent escalating project costs and to maintain healthy market competition. Access to technology facilitates access to energy, thus ensuring reliable energy availability and energy security.

The potential impact of large-scale GH2 production on agriculture and water and food security must not be overlooked and will require a delicate balance between competing demands for limited natural resources. Comprehensive environmental and social impact assessments are paramount in this context. Suggesting possible revenue- and benefit-sharing mechanisms, the report underscores the fundamental role of social contracts in ensuring an equitable distribution of benefits.

Stimulating market creation and demand for green goods

Governments have substantial influence in creating initial demand for green goods produced with GH2, such as green steel. By prioritizing green goods over traditional products in their public procurement activities, governments can boost demand, support GH2 producers and set a precedent for others to follow. This approach can complement direct subsidies for green goods produced with GH2, with government funding serving as a market shaper rather than a mere hand-out. Additionally, public procurement can consider the local content of goods, giving preference to those with a higher share of domestically manufactured components and local employment. Reliable certification measures are necessary to ensure added green value, i.e. low carbon emissions, of the goods manufactured with GH2, justifying the initial price gap to conventional products.

Policymakers will also need to address market distortions, particularly those arising from fossil fuel subsidies that have an impact on the GH2 sector. To promote the use of GH2 in downstream industries, incentives such as price premiums and tax rebates can be introduced. Additionally, the implementation of quotas and targets represents a viable mechanism to establish a baseline for GH2 use in specific market segments, ensuring the fulfilment of CO_2 intensity objectives.

Infrastructure, transport and storage solutions for GH2

Formulating comprehensive, long-term strategies for the transport of GH2 with a focus on efficient and standardized regulations that govern the planning, financing and safety will be key for enabling developing countries to participate in international trade, particularly in the context of cross-border transport. This report discusses the most important questions policymakers must address when planning GH2 infrastructure, ranging from the balance between privately owned infrastructure and open-access systems, the selection of domestic storage solutions and the strategic location of electrolysers and storage facilities. It emphasizes the socioeconomic dimension of GH2 infrastructure development and the need to prioritize the resilience and livelihoods of local communities.

The report examines the feasibility and challenges associated with pipeline construction and maritime transport, exploring alternative energy carriers such as liquefied hydrogen (LH2), ammonia (NH3) and liquid organic hydrogen carriers (LOHCs) as potential solutions for long-distance trade. Moreover, the establishment of storage facilities will be crucial for ensuring reliable GH2 supply, particularly in response to fluctuations in renewable energy generation. Securing investments for retrofitting existing natural gas networks and building new dedicated hydrogen infrastructure is essential. This can be achieved through various financing options, including public procurement, de-risking measures, public-private partnerships and regulated asset base models.

Global partnerships, international collaboration and financing strategies for GH2

The rapid scaling up of global green hydrogen production calls for multilateral cooperation in science, technology and innovation. International collaboration is crucial to facilitate research on the environmental impacts of hydrogen and to develop methods to mitigate hydrogen leakage. International organizations, such as UNIDO, IRENA, IEA and the World Bank, amongst others, are pivotal contributors to research and knowledge dissemination in this context. Knowledge sharing is essential to bridge disparities in hydrogen know-how and foster well-informed decision-making among policymakers.

To achieve the goals set forth in the Paris Agreement, a substantial increase in international climate financing is imperative, with a significant share earmarked for GH2 projects. Policymakers around the globe should aim to lower the cost of capital for GH2 projects, involving development finance institutions, and establishing a transparent and predictable regulatory framework. UNIDO and the World Bank are mapping out financial support offered by development banks for hydrogen projects. The development of international standards and certifications for hydrogen emissions, safety and operations is crucial for fostering market growth. International organizations such as ISO and UNIDO are actively working towards formulating such standards, with a particular emphasis on ensuring the participation of developing countries and active engagement in standard-setting processes. This entails developing technical capacity and harmonizing certification methodologies.

International collaboration is essential for establishing early GH2 trade corridors. Such collaboratve efforts are crucial for pooling resources, sharing knowledge, setting common standards and accelerating the development of hydrogen infrastructure, which can mitigate the risks of isolated efforts and fragmented initiatives. Moreover, adopting a unified approach to green financing and green product standards will bolster the bankability of GH2 projects. While reaching a global consensus on these unified approaches will be challenging, it is indispensable for realizing a GH2 roll-out that delivers benefits to both people and the planet.

1. INTRODUCTION

In pursuit of their commitment to achieving the goals set forth in the Paris Declaration, countries and businesses around the world are actively exploring sustainable and clean energy alternatives. Green hydrogen (GH2), namely hydrogen derived from renewable energy sources, is gaining widespread recognition as the preferred choice for a number of applications.

1.1. Why green hydrogen?

GH2 is being championed as the fuel of the future for being clean, storable and portable (IRENA, 2020a). When combined with oxygen, hydrogen combusts to produce water and releases heat without emitting carbon dioxide (CO_2). Due to hydrogen's high energy density, it is ideal for fuelling energy-intensive industrial processes that are difficult to electrify and can furthermore be used as feedstock for a number of industrial applications. Moreover, as a clean energy carrier, GH2 can be stored for extended periods with minimal losses. Compared to grid-connected renewable electricity, it can be more flexibly tran
large distances to applications farther afield from the renewable energy source.

Blue hydrogen, which is produced with fossil fuel and carbon capture and storage (CCS), can serve as an initial catalyst for the hydrogen market during the energy transition's early stages. Greenhouse gas (GHG) emissions from existing facilities can thus be reduced while continuing to use current infrastructure. Blue hydrogen comes with certain limitations, however: it relies on finite resources, is susceptible to fossil fuel price fluctuations, is tied to the costs and monitoring of CO_2 transport and storage, and does not enhance energy security. Moreover, the efficiency of CCS is suboptimal as it is still associated with some residual CO_2 emissions, and the use of methane in CCS may give rise to upstream leakage, rendering blue hydrogen incompatible with net-zero emission goals.

1.2. Identifying potential GH2 producers

GH2 production is a viable option for countries endowed with abundant solar and wind power potential. The IEA (2023a) identifies many low- and middle-income countries in Africa, the Middle East, Southern Asia and the western regions of South America as the most promising sites for GH2 production due to their abundance of solar and wind energy. Most of these countries currently have very limited renewable energy production capacity and substantial efforts will therefore be necessary to increase it and to decarbonize their CO_2-intensive electricity grid before entering into GH2 production.

1.3. Exploring GH2 applications

GH2 will not replace the decarbonization of the power, transport, heating and cooling industries achieved through electrification from renewable energy sources, but rather complement it. Figure 1.1. presents applications where GH2 and its derivatives provide a distinct comparative advantage, namely:

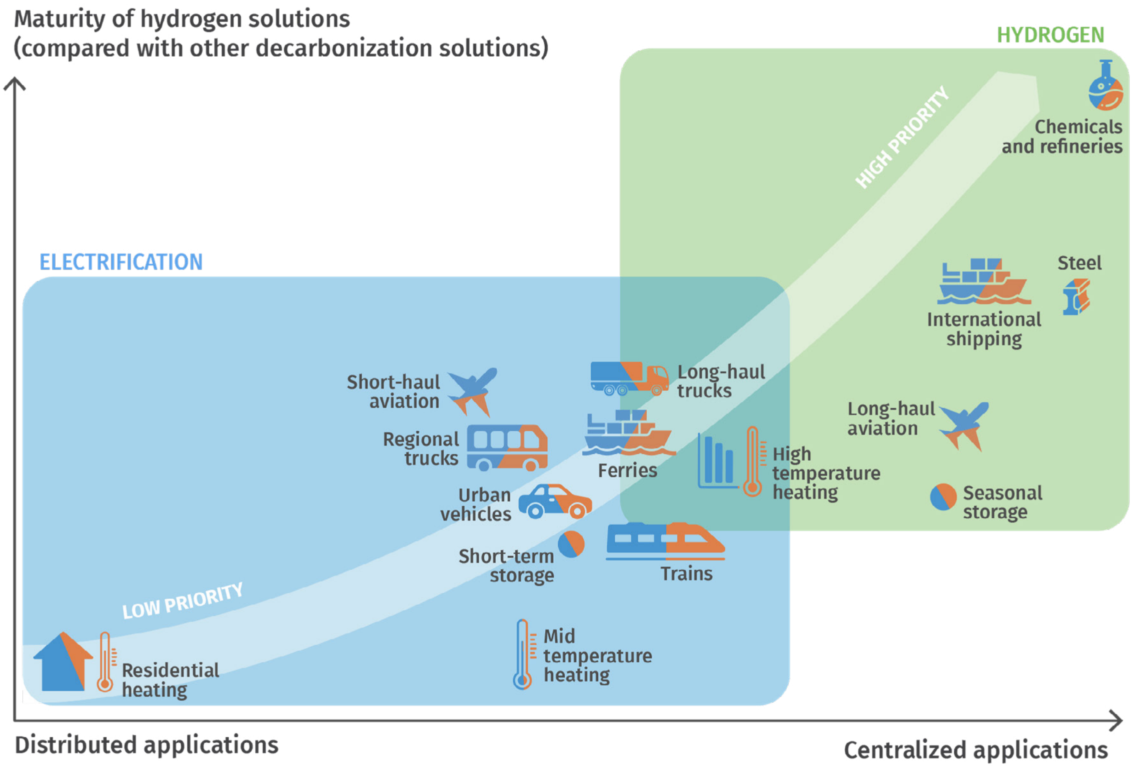
Hard-to-abate industries. Heavy industry currently uses hydrogen derived from fossil fuels, particularly in oil refinement and the production of ammonia, methanol and steel. Using GH2 as a high-grade heat fuel can contribute to the decarbonization of these and other hard-to-abate industries. In addition, it can serve as feedstock for a number of industrial applications.

Aviation and maritime transport. Hard-to-abate transport industries, such as shipping and aviation, are difficult to decarbonize due to the limited availability of low-carbon fuel alternatives.

Energy. As an efficient energy carrier with long-term storage capabilities without significant losses, hydrogen can play a pivotal role in stabilizing energy grids that rely on solar and wind power. By mitigating the fluctuations inherent in these renewable energy sources, hydrogen can help ensure a consistent and reliable supply of electricity.

Cost competitiveness and infrastructure availability will be key determining factors in the adoption of additional hydrogen applications. For example, the use of hydrogen fuel cell vehicles and trucks will be contingent on fuel cell costs and the availability of refuelling stations. Hydrogen can be integrated into existing natural gas networks and used in district heating systems or in hydrogen boilers and fuel cells for residential heating systems. Ammonia, on the other hand, has the potential of enhancing power system flexibility when used in gas turbines or can contribute to emissions reductions of coal-fired power plants.

Figure 1.1. Policy priorities for GH2 applications



Source: IRENA, 2022a

Note: The end uses are located on the x-axis according to estimated average daily hydrogen demand for industry, refuelling stations and combustion devices with a power relationship. The end uses are located on the y-axis according to the differences between the technological readiness levels of hydrogen-based vs electricity-based solutions. This is not a static picture and priorities may change over time depending on advances in technologies.

1.4. Global demand and the hydrogen industry's future outlook

In 2022, about 95 million tonnes (Mt) of hydrogen were produced globally, with the majority generated through processes that rely on fossil fuels such as natural gas and coal, also known as "grey hydrogen". Grey hydrogen was primarily used in industrial applications such as crude oil refining, ammonia production and methanol synthesis, which collectively account for nearly 93 per cent of total hydrogen consumption (IEA, 2023a).

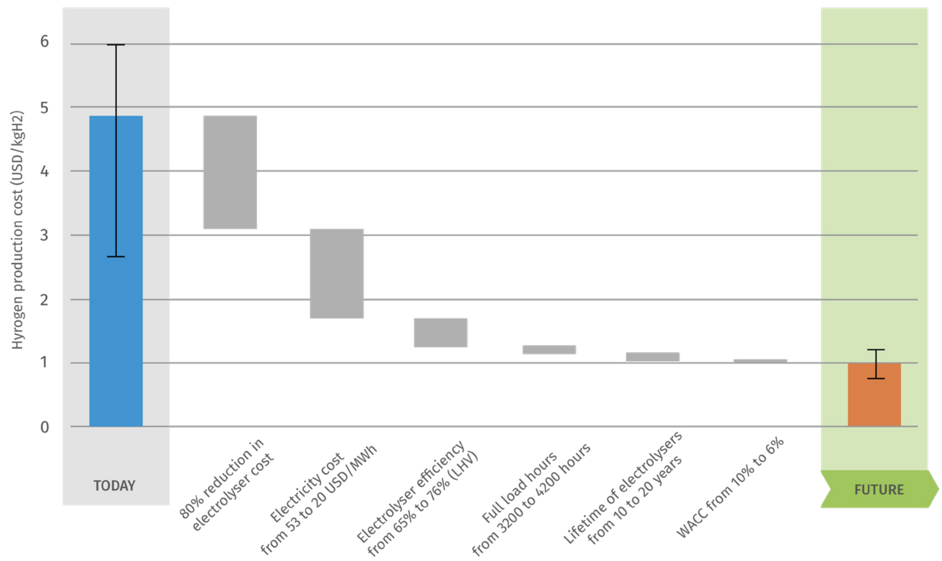
According to the International Renewable Energy Agency (IRENA, 2023c), GH2 is expected to play a significant role in the energy transition towards the 1.5°C climate goal by 2050. IRENA's World Energy Transitions Outlook 2023 projects a substantial increase in global GH2 production, reaching approximately 492 million tonnes by 2050. As part of the transition strategy, however, some residual blue hydrogen production, totalling around 31.5 million tonnes, will be inevitable (IRENA, 2023c).

1.5. A price forecast for GH2

Significant reductions in the costs of GH2 production will be necessary to unlock its full potential. Its production costs are currently 3 to 6 times higher than for grey hydrogen (USD 3-6/kg vs USD 1-2/kg), even in the most favourable production sites. One major cost factor is the renewable electricity required to power electrolysers. GH2 produced in locations with abundant renewable resources can enhance its cost competitiveness. The cost compression of solar photovoltaic (PV) and wind technologies will also contribute to lowering the costs associated with GH2 production.

Another priority is lowering the cost of electrolysers, which could potentially lead to an 80 per cent reduction in investment costs in the long term. Among others, this could be realized by increasing the size of electrolysis plants to achieve economies of scale; automating manufacturing to improve efficiency; optimizing material sourcing to reduce reliance on scarce materials such as iridium and platinum; enhancing durability; improving operational efficiency and flexibility; customizing electrolysis systems for specific industrial uses, and leveraging learning rates to drive down costs.

Figure 1.2. Hydrogen cost forecasts



Source: IRENA, 2020a

Note: "Today" captures best and average conditions. "Average" signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value -LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). "Best" signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

1.6. What are the prospects for renewable-rich developing countries?

GH2 production provides countries with abundant renewable energy resources the opportunity to strengthen their energy security and to reduce their vulnerability to external shocks. They will have the possibility to participate in the global hydrogen market, which is projected to account for around 25 per cent of total hydrogen demand by 2050. According to IRENA's 1.5°C scenario (2022b), around 55 per cent of internationally traded hydrogen will be transported through pipelines. GH2 production in renewable-rich will open up new avenues for achieving net-zero industrial development and creating local value addition, leading to job creation, skills upgrading, investment mobilization and wealth generation. In short, engaging in GH2 production has the potential of reinforcing developing countries' overall economic resilience and facilitating the development of diversified and knowledge-based economies.

1.7. Overcoming the challenges of technological barriers and high production costs

Countries face several obstacles to fully leverage GH2's potential. The biggest challenges include the necessary technological know-how to produce GH2, the scaling up of renewable energy generation and electrolyser capacities, the high production costs, lack of domestic markets and limited infrastructure. Targeted policies and collaborative efforts are therefore necessary to successfully address these barriers to GH2 production. Moreover, demand for and the supply of GH2 will have to be simultaneously promoted. Policymakers have a crucial role to play in driving innovation, attracting private sector investment, and in forging partnerships to effectively integrate hydrogen into their country's energy mix.

1.8. Harnessing the transformative potential of GH2

Governments, international organizations and private enterprises around the globe have launched ambitious initiatives and policies to support the development and use of GH2. These efforts entail strategies to promote research and development (R&D), facilitate infrastructure development, and to create supportive regulatory frameworks for the widespread adoption of GH2 technologies. While Japan was the first country to develop a national hydrogen strategy (NHS) in 2017, over 45 countries—primarily developed countries in Europe—have since published NHS as well. Developing countries are rapidly catching up, with around 40 per cent of currently published NHS attributed to this country group. However, as of October 2023, no transition economy or least developed country (LDC) had published a NHS (Figure 1.3)

This report explores various facets of policymaking from the perspective of renewable-rich developing countries to promote the development and adoption of GH2 as a sustainable energy option. It addresses what can be described as the "hydrogen deadlock" which entails four key components: (i) supply, (ii) demand, (iii) infrastructure, and (iv) international context/coordination. There is a clear need for comprehensive policies and strategies in developing countries to create and sustain demand for GH2. Policies that have been implemented in the past to promote renewable energy efficiency and the manufacturing of green goods can be adapted to factor in GH2; by focusing on market creation and leveraging existing policy frameworks, policymakers can foster GH2's growth as a viable energy solution.

The report provides guidance for effective policymaking along the GH2 value chain. While existing literature comprehensively reviews policies for increasing renewable energy generation, this report focuses on other important areas such as the production of GH2, its transformation, GH2 transport infrastructure and the creation of domestic demand for GH2. In addition, it highlights international cooperation as a crucial factor for supporting national policymaking efforts. The report concludes with policy sheets that offer concise guidance for policy design at every stage of the GH2 value chain.

Figure 1.3. Cumulative number of NHS by UN country classification and year of first publication

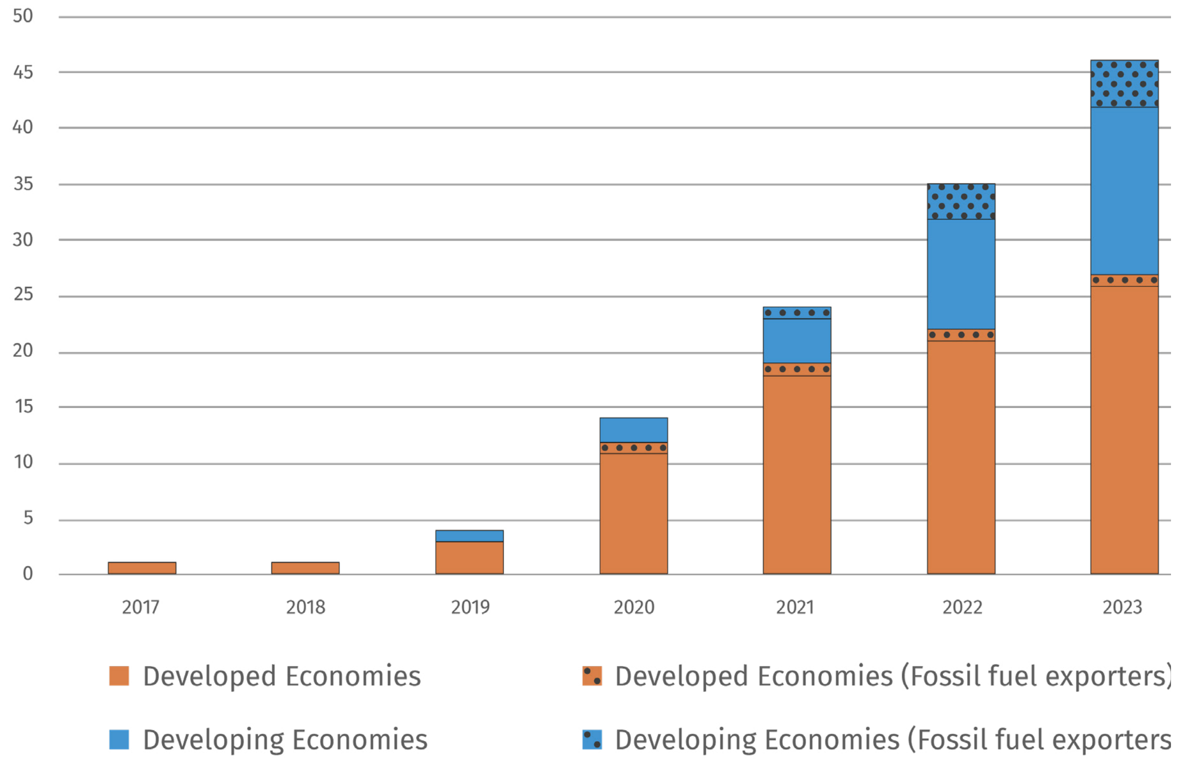
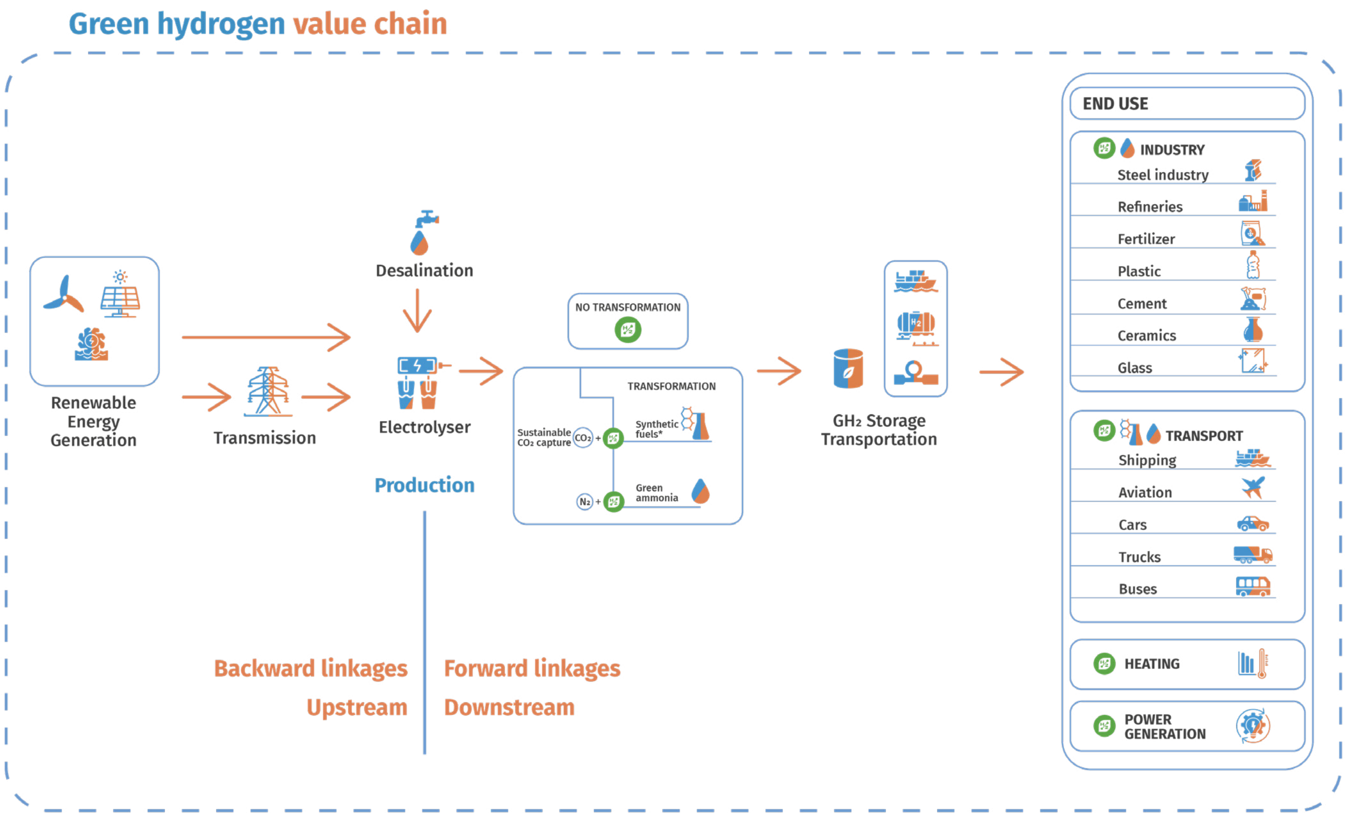


Figure 1.4. GH2 value chain linkages



Chapter 2 reframes the current hydrogen discourse away from "producing for export" by shedding light on the value creation prospects for hydrogen-producing countries. That is, countries should not exclusively rely on GH2 exports considering the high technological and systemic uncertainties these entail, but should instead pursue the development and implementation of a gradual, phased and integrated GH2 strategy. This requires the establishment of a domestic hydrogen market to decarbonize existing industries and plans to export any surplus GH2. Governments should prioritize attracting investments in energy-intensive steel or base chemicals with the aim of gradually moving into downstream industries that use green steel or chemical feedstock, and integrate into upstream industries that produce renewable power generators and electrolysers. Such a long-term vision calls for restructuring and aligning the country's energy, infrastructure, trade and industrial strategies and policies with one another.

Chapter 3 explores GH2 production in more depth with a focus on GH2's backward linkages, its production's core activities and their connections to upstream industries. The chapter provides valuable insights into strategies for attracting renewable energy investments for GH2 production, which requires reliable electricity supply for electrolysers, and addresses concerns related to technology acquisition, risk mitigation and the local manufacturing of GH2 hardware. Additionally, policy measures that can facilitate the widespread deployment of electrolysers and renewable energy sources are discussed. The socioeconomic dimension of GH2 production projects is raised as well, highlighting the importance of effective policymaking in regulating and governing water and land resources.

Chapter 4 focuses on the role of industrial policy in facilitating the development of a domestic hydrogen market. It introduces a range of targeted policies designed to stimulate domestic GH2 demand and to promote its integration in the value chain. The chapter emphasizes the need for comprehensive regulations, early mover support, demand generation mechanisms, and effective strategies for value chain coordination. It also discusses the pivotal role local market creation plays in driving the adoption and use of GH2 as a clean energy solution.

In Chapter 5, a comprehensive analysis of current technologies and associated challenges is presented, with a focus on the intricate planning required for the development of hydrogen grids and infrastructure. Additionally, it reviews the necessary policies to bolster this crucial segment of the GH2 value chain.

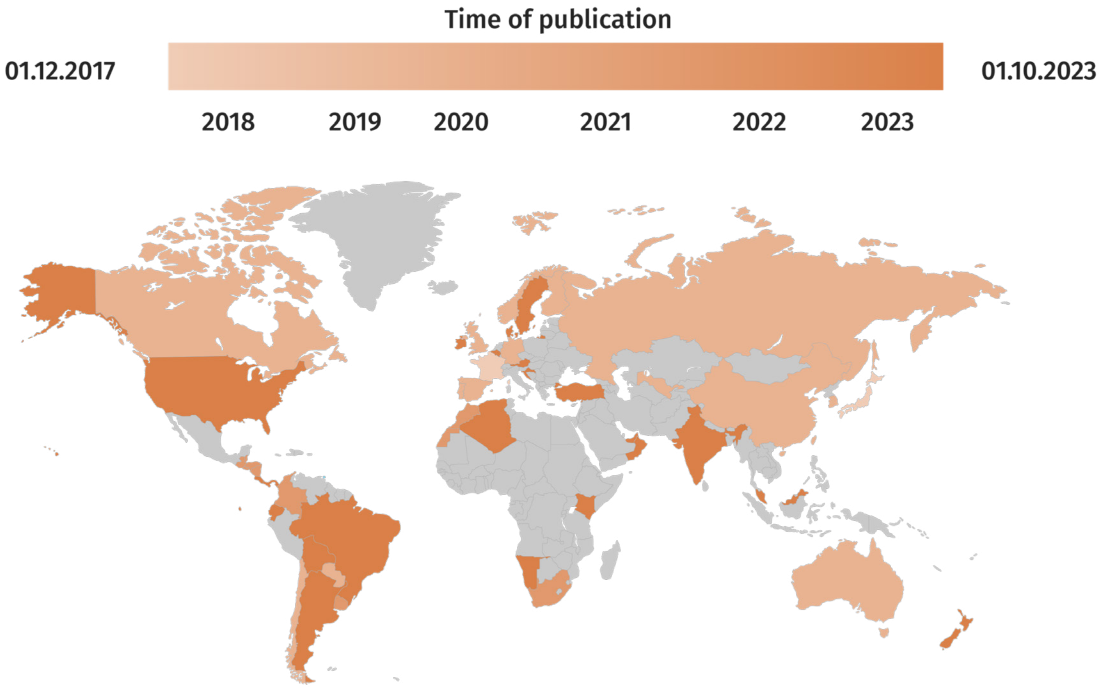
Chapter 6 focuses on the importance of promoting collaboration between governments, industry stakeholders and academia to effectively navigate the complexities of the GH2 industry and how to capitalize on the opportunities it presents. It explores different strategies including co-financing policy frameworks, knowledge sharing initiatives, intergovernmental agreements, financing support, optimal import-export coordination and green product trade policies. By aligning a range of policies with one another, mobilizing resources and by embracing innovation, the production and adoption of GH2 can be significantly accelerated, unlocking a future that is powered by clean and sustainable energy.

The report concludes with concise policy sheets that offer pragmatic guidance for policymakers. They summarize areas for policy intervention, including the underlying objectives of such interventions, key actions, potential tools, actor involvement and connections with other policies. These recommendations provide a clear policy direction for promoting project inception, developing a NHS, establishing regulatory standards and creating a conducive business environment. The concluding chapter also emphasizes the importance of supporting early movers by facilitating access to resources and promoting entrepreneurial activities. Additionally, it outlines mechanisms for stimulating commercial demand for GH2, implementing certifications and seamless value chain integration. Finally, it highlights knowledge co-creation and exchange through targeted educational initiatives, knowledge sharing platforms and digital government resources.

2. The GH2 industry: reframing the narrative

The current global discourse on GH2 mostly reflects the perspective of the Global North. The mission-oriented policymaking of early movers through supportive (e.g. the U.S. Inflation Reduction Act) and mandating (e.g. the EU's Delegated Acts) industrial policies has significantly influenced the GH2 market's growth in developing and emerging economies. Major import hubs, especially Germany, Japan and the Republic of Korea, have established numerous partnerships with developing countries, reflecting the important role they play in international GH2 trade. This message has resonated more clearly in recent years: while the majority of NHS prior to 2022 had been published in the Global North, an increasing number of countries from the Global South have joined the ranks of economies planning to produce and use GH2 (see Figure 2.1.).

Figure 2.1. Publication of NHS by year of publication and region



This report takes the perspective of countries in the Global South on GH2 development and shifts the emphasis of the current narrative from **"the relevance *of* developing countries *in* the future GH2 market"** to **"the relevance *of* the future GH2 market *for* developing countries".**

The exclusive focus on GH2 as a developing country export has raised concerns about the fair distribution of GH2's benefits, sparking increasing resistance within local communities in these countries. This report thus delves deeper into the potential advantages of GH2 production for developing countries, and explores strategies to navigate and mitigate the risks involved in this transformative venture.

2.1. Envisioning the role of GH2 in developing countries

Since the publication of Japan's NHS in 2017, over 45 countries—including around 40 per cent from the Global South—have followed suit by releasing their own strategies, roadmaps and action plans to develop and use GH2. Although these plans differ in terms of targets and measures, they address similar issues that arise in relation to the creation of a sustainable GH2 market, such as the drivers of GH2 production; the goals for domestic use and international trade; sustainability and inclusive participation, and the need to overhaul the current socioeconomic system. We have identified ten key insights based on an analysis of these documents:

1. **Countries invest in GH2 for various reasons:** participation in the international trade of GH2 and its derivatives; decarbonization of the economy; energy supply security and diversification; acceleration of innovation and industrial growth, and social and environmental (co-)benefits.

2. **GH2 production.** Countries are leveraging their local conditions and natural factor endowments. While most countries prioritize the development of hydrogen from renewable energy sources such as solar and wind through electrolysis, they are also exploring other clean production methods.

3. **Some countries are focusing on developing their domestic market before engaging in GH2 trade.** Several countries have already identified specific "no-regret" applications that can be easily adapted to GH2, such as ammonia production for fertilizers, methanol as feedstock and synthetic fuels for maritime transport. Other NHS prioritize exports, foreign direct investment (FDI) and the implementation of large-scale hydrogen projects.

4. **GH2 fosters industrial development and innovation.** While the decarbonization of hard-to-abate industries features prominently in many NHS, countries also emphasize the potential of creating new sustainable industries such as fertilizer and steel, and gaining a competitive advantage or even assuming leadership in hydrogen technologies, including electrolysers and fuel cells.

5. **Most countries prioritize a gradual and sequenced approach** to GH2 production and use. They start with small- to medium-scale projects on both the supply and demand side.

6. **The development of GH2 calls for a comprehensive overhaul of the socioeconomic system.** Countries recognize that the technological novelty and capital-intense nature of GH2's value chain necessitate coordinated policymaking across various policy areas, including education and training, infrastructure, and industrial and structural policies aimed at facilitating a fair and sustainable expansion of the domestic market. Some NHS also outline financial support mechanisms.

7. **Countries recognize the potential risks associated with GH2 production for the environment and society**. Some countries emphasize a balanced use of land and water resources, while others promote a circular economy and a reinvestment of revenues from the GH2 value chain into local communities.

8. **Stakeholder and civil society engagement play a crucial role in increasing acceptance of GH2 technologies**. Inter-ministerial working groups that include civil society, private and public stakeholders are being established and technical roundtables organized that involve enterprises, industry associations, universities and research institutions to promote acceptance of new GH2 technologies. Additionally, advisory boards that include public policy and climate action experts have been created, and regular consultations with industry and affected communities are being conducted. National hydrogen councils and associations serve as focal points for GH2 strategy development.

9. **Bold policy actions are needed in the short term to ensure successful market ramp-up for GH2**. While the market economy plays a pivotal role, exclusive reliance on the market alone does not

suffice given countries' ambitious decarbonization targets and the coordination challenges. NHS typically focus on mid- to long-term goals (2030, 2040 and 2050), but also include updates and action plans for the short term to continuously adapt to the dynamic nature of technology and market trends.

10. **Hydrogen trade objectives are often linked to international collaboration.** The majority of NHS highlight countries' potential role in future international hydrogen trade, including imports, exports and achieving self-sufficiency. Some country strategies identify specific regions for promoting trade partnerships. International cooperation plays a crucial role in targeted actions such as knowledge exchange, technology transfer, collaboration in hydrogen technology R&D and in international standard-setting. While many NHS emphasize international collaboration, regional partnerships are not always given the same prominence, despite their relevance in ramping up the hydrogen market at the global scale.

Table 2.1. Topics mentioned in NHS

Aspects	Measures/areas mentioned	Country examples
Key drivers	Participate in international trade of hydrogen and its derivatives	Uruguay, Namibia
	Decarbonize the economy	Chile, Türkiye
	Strengthen energy security	China, India
	Diversify energy supply	Germany
	Innovation and industrial development	Namibia, Uruguay
	Environmental and social (co-)benefits	Chile, South Africa
Identification of "no-regret" areas	Ammonia production for fertilizers	Türkiye, Kenya
	Methanol production as feedstock	Uruguay
	Steel production	South Africa
	Maritime shipping	Chile
Quality infrastructure	Safety standards	Chile, China
	Regulation of hydrogen storage	India
	Adoption of international technical standards for hydrogen	Columbia
Financial support mechanisms	Direct incentives, extension of subsidies, fee waivers, grants	India
Environmental sustainability	Balanced use of land and water resources, circular economy	Chile
Participation	National GH2 advisory group comprising experts from academic and research institutions, industry and civil society	India
Time frame	Development of GH2 use until 2035, projected in three waves; update of NHS every three years	Chile
International collaboration	International cooperation	China
	Regional cooperation	Uruguay

2.2. Unravelling the benefits and barriers of GH2 trade

As already briefly mentioned above, there are several compelling reasons why renewables-rich developing countries should actively participate in GH2 production and trade:

1. **The global effort to decarbonize hard-to-abate industries** that cannot be easily electrified is reliant on the involvement of developing countries with abundant renewable resources. International hydrogen trade can support the decarbonization efforts in both exporting and importing countries.

2. **Export revenues enhance the trade balance and facilitate access to foreign currencies.** The projected interregional trade of GH2 in 2050, estimated at USD 280 billion, is anticipated to generate over half of its economic activity from developing countries (Deloitte, 2023). This burgeoning trade has the potential to trigger a cascading effect on economic development, fostering local activities and job creation.

3. **Hydrogen trade empowers countries within a democratically structured global energy landscape**, providing producing countries increased autonomy, strengthening their economic networks and elevating their political significance. Additionally, it offers fossil-fuel exporting countries the opportunity to retain some of their export revenues and maintain political influence (IRENA, 2022e).

4. **GH2 exports can facilitate domestic energy transitions** by integrating renewable energy into the national energy grid. Such integration not only drives down the cost of renewable energy in the country of production, but also improves energy access and affordability for the local population.

5. **The trade of GH2 and its derivatives can prevent stranded assets in both exporting and importing countries**. By supporting the local decarbonization of industries in the exporting country, GH2 exports can help avoid the implementation of conventional, fossil-based projects that could become stranded assets in the future. The technical components of the coal-based blast furnace-basic oxygen furnace (BF-BOF) in steel production, for example, have lifetimes of between 40 years and 60 years, exposing them to carbon lock-in and stranded asset risk by 2040 (Agora Industry and Wuppertal Institute, 2023). The production of GH2 may not be cost-competitive in the importing country in the long term due to the country's scarcity of renewables. Therefore, importing GH2 or green intermediates such as direct reduced iron (DRI) can help prevent reliance on costlier and less sustainable alternatives.

6. **International GH2 trade can facilitate knowledge transfer and spillovers, thereby accelerating socioeconomic development in GH2 exporting countries**. GH2 trade is creating a new global division of labour and is generating jobs and value in regions with abundant renewable resources. While certain key technologies such as electrolysers are likely to be supplied by regions with limited renewable energy sources (Verpoort et al., 2023), the overall expansion of technological capabilities and industrial capacities will bolster domestic research, development and innovation in GH2 exporting countries.

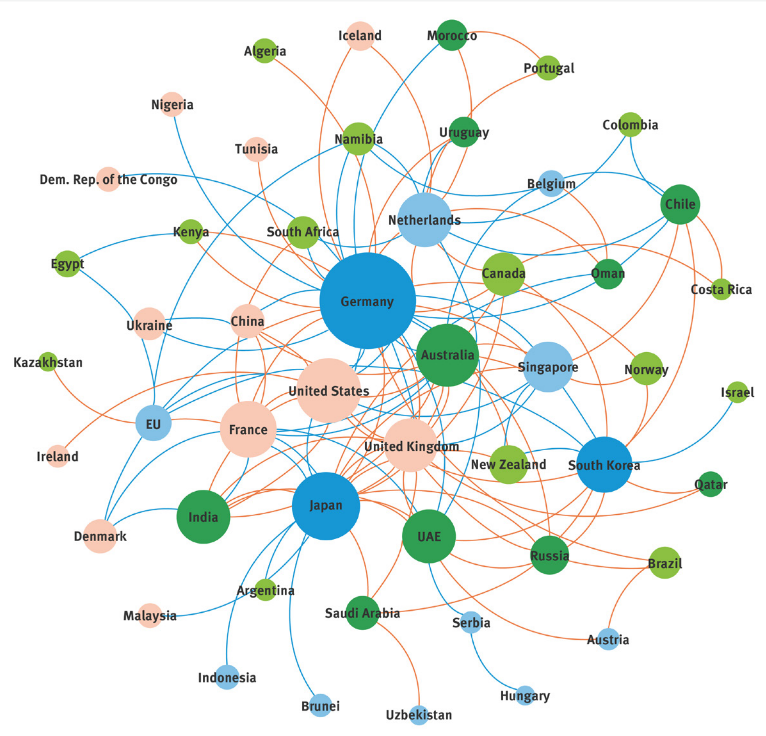
To accelerate the global growth of the hydrogen market, **hydrogen partnerships** have been established between potential exporting and importing countries (see Box 2.1).

Yet, despite the ambitious goals associated with **the GH2 market, its growth has been slow. In 2022,** less than 100 kilotons of hydrogen from electrolysis were produced, falling far short of the expected demand by 2050 (IEA, 2023a). If all the announced electrolysis projects—including those at very early stages of development—are realized, GH2 production could reach around 27 Mt by 2030. Latin America, particularly Chile, Brazil and Argentina, could account for nearly 6 Mt of production, while African countries, including Kenya, Mauritania, Morocco, Namibia and South Africa, could produce about 2 Mt by 2030 (IEA, 2023a). The majority of GH2 projects are still in their infancy, with only a few projects currently underway (see Table 2.2). This is particularly true for export-oriented projects, where less than 25 per cent of planned projects until 2030 have reached the feasibility stage. Moreover, two-thirds of the projected export capacities still lack potential buyers, and only a few projects have signed binding off-take agreements (IEA 2023a).

Cost challenges pose a significant obstacle to the rapid development of GH2 projects in developing countries. The high capital costs associated with renewable energy and the expansion of electrolysis, coupled with risks related to political stability, regulatory frameworks and bureaucratic procedures such as licensing and land acquisition, undermine the bankability of projects and prevent their timely implementation, especially in developing countries. Demand-side stakeholders often adopt a cautious "wait and see" approach, resulting in a lack of off-take agreements.

Box 2.1. Global Hydrogen Partnership Network

Figure 2.2. Visualization of the global hydrogen partnership network



Demand for GH2 is particularly high in Germany, Japan and the Republic of Korea. These economies have actively forged hydrogen partnerships with potential exporting countries. Germany has signed Memorandums of Understanding (MoU) with countries in sub-Saharan Africa (e.g. South Africa, Namibia), Latin America (e.g. Chile), the MENA region (e.g. Morocco, Saudi Arabia, Egypt and the United Arab Emirates). On the other hand, Japan and the Republic of Korea are focusing on Oceania, South America and North Africa to find suitable partners. On the export side, Australia, India, the United Arab Emirates (UAE), Saudi Arabia, Chile and the Russian Federation have also established a robust network with other countries. Even countries that will not necessarily rely heavily on GH2 trade in the future, such as the United States, the United Kingdom, France and China, have entered into partnerships.

Source: Analysis based on data from the World Energy Council Germany (2023), World Energy Council (2022, p.7), and own research

Note: Green shades refer to (slightly and strongly) export-oriented countries, blue shades to (slightly/strongly) import-oriented countries, while light red colour indicates a neutral or rather self-sufficient position of countries.

The international transport of GH2 is still fraught with technological and regulatory uncertainties, which impedes its cost-effective transport in line with technical and environmental standards (see Chapter 5). Maritime transport of hydrogen (including conversion and re-conversion) can raise the landed costs of hydrogen significantly, placing countries located outside the pipeline distance from major import hubs at a comparative disadvantage.

The scale and dynamics of GH2 hydrogen trade remain uncertain. According to IRENA's (2022b) 1.5°C scenario, around 25 per cent of hydrogen production could be internationally traded by 2050, with about half transported through pipelines. Importing countries, driven by energy diversification and security concerns, are increasingly pursuing self-sufficiency and friend-/ neighbour-shoring. Recent reports highlight, for example, the considerable renewable energy potential and GH2 production within Europe's borders (e.g. Quitzow et al., 2023). Policy frameworks that harness GH2's domestic potential in industrialized economies may discourage investment in developing countries that lack comparable subsidy schemes.

Blue hydrogen, which serves as a transitional technology, could extend the timeline of GH2 adoption. Major importing countries such as Germany are increasingly considering the use of blue hydrogen as a transition technology. While blue hydrogen may accelerate GH2 use and facilitate the transition to a GH2 future in the medium term, it is not fully emission-free and carries the risk of "lock-in". In the short term, GH2 exporters, especially those relying on maritime transport for international trade, may find it difficult to compete with the price of blue hydrogen. This might represent challenges for developing countries that are heavily reliant on GH2 exports, potentially jeopardizing the viability of GH2 initiatives in these countries, failed GH2 projects could lead to political frustration and societal backlash against further decarbonization projects, consequently delaying the overall green industrial transformation in these countries. **Establishing a strong business case within these countries' economies** is therefore crucial. This will enhance their resilience in anticipation of a global market expansion which at present remains uncertain.

Table 2.2. **GH2 projects at advanced stages of development.** (Source: IEA, 2023b)

Project	Country	Status	End Use	Description
Helios Green Fuels – NEOM	Saudi Arabia	FID	Ammonia	The Neom Green Hydrogen Company, a joint venture between ACWA Power, Air Products and NEOM recently achieved financial close on 22 May 2023, with a total investment value of USD 8.4 billion. The world's largest GH2 plant will be located in Neom and is projected to generate up to 600 tonnes per day of green ammonia for export from 4GW of solar and wind energy by the end of 2026. An exclusive 30-year off-take agreement has been concluded with Air Products. Over two-thirds of the investment value are financed from 23 local, regional and international banks and financial institutions.
Masdar City – Green Falcon	United Arab Emirates	FID	Synfuels	TotalEnergies, Masdar, Siemens Energy and other companies are collaborating to establish a demonstrator plant in Masdar City to produce sustainable aviation fuel (SAF) from GH2. The demonstration project should pave the way to commercial production of SAF.
Cleanenergy Solutions Namibia	NAM	FID	Mobility	The Ohlthaver & List (O&L) Group and CMB.TECH launched the Cleanenergy Solutions Namibia joint venture to construct Namibia's first GH2 production plant in February 2022. The demonstration plant is based in the Erongo region and is expected to become operational by the end of 2023 and produce green ammonia as transport fuel. It is to be followed by a 10-hectare solar park, equipped with a 5 MW electrolyser. Environmental studies have been carried out, and the funding has been approved by the government.
OCP green ammonia	Morocco	Under construction	Ammonia	Morocco's OCP, one of the world's largest phosphates and fertilizer companies (and an importer of ammonia) is currently developing a green ammonia demonstration plant jointly with Green Energy Park (GEP) and Fraunhofer IGB. The demonstration plant has a capacity of four tons a day which is used for testing electrolyser technologies and ammonia synthesis in a realistic intermittent operation and on an industrial scale.
Unigel, phase I	BRA	Under construction	Ammonia	Brazil's largest fertilizer producer Unigel launched the country's first industrial-scale green hydrogen and ammonia project in Camaçari, Bahia province. 60,000 tonnes of ammonia are to be produced from 60 MW of grid-connected renewable energy (RE) per year, using Thyssenkrupp nucera electrolysers. Operational by 2023, it will quadruple production during the second phase up to 2025.
Haru Oni, phase I	Chile	Operational	Methanol, synfuels	Siemens Energy, Porsche, Enel, ExxonMobil, Enap and others have built the world's first integrated industrial-scale plant for synthetic fuels in Patagonia. Large-scale production was planned to start in April 2023. Two wind turbines at Haru Oni can create the same amount of e-fuel as around six wind turbines in Germany. The facility is expected to produce up to 550 million litres of e-fuel in coming years.
Sinopec – Kuqa	China	Operational	Refining, transport	Sinopec Xinjiang Kuqa GH2 pilot project entered operation in July 2023. The solar-to-hydrogen project produces up to 20,000 tonnes per year of GH2, along with the capacity to store 210,000 m^3 of hydrogen (H_2) and transport 28,000 m^3 of H_2 per hour. With a focus on hydrogen transport and green hydrogen refining, Sinopec also installed over 100 hydrogen refuelling stations to accelerate GH2 development.

2.3. The potential of GH2 to transform industrial development

The shift in the prevailing narrative highlights the significance of GH2 production for developing countries, emphasizing the economic opportunities it presents throughout the value chain (see Fig. 2.3). By engaging in both upstream and downstream activities of GH2 production, developing countries can generate sustainable employment; add long-term value; enhance their international competitiveness, and mitigate risks associated with participation in global hydrogen trade.

The hydrogen value chain comprises seven primary activity clusters or windows of opportunity (Stamm et al., 2023), which can be pursued simultaneously or in any preferred sequence.

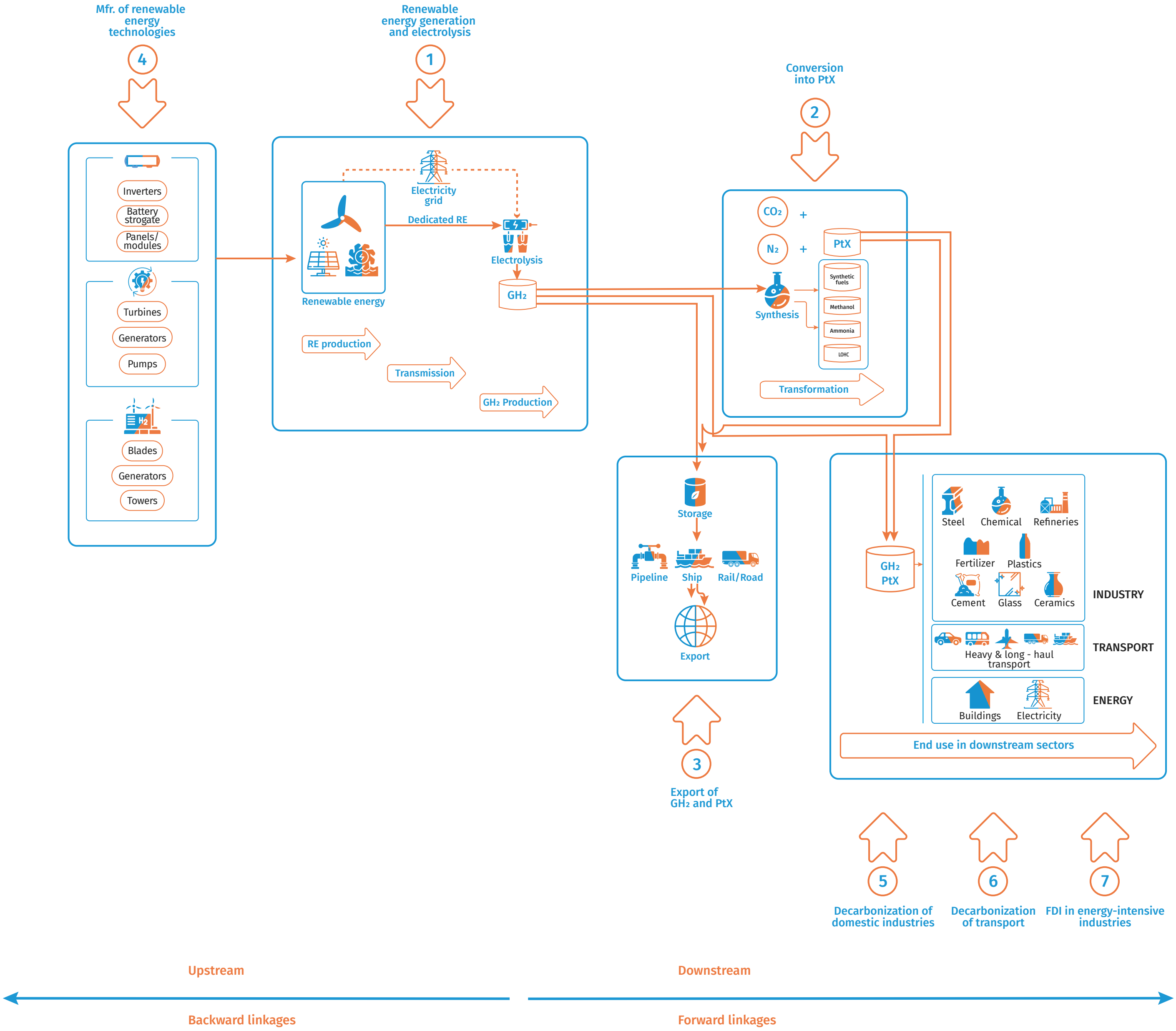
1. **Renewable energy generation and electrolysis.** GH2 production requires initial investments in renewable energy sources such as solar and wind farms and in geothermal and hydroelectric installations, which are contingent on regional resource endowments. Electric grids need to be developed, electrolysers installed and pipelines and tanks for water and hydrogen transportation established. Water-scarce regions may also need to build and operate desalination plants. These activities are capital-intensive and often require large-scale production, making it challenging for newcomers to enter the market. In most developing countries, foreign investment and imported technologies are likely to dominate these activities. However, significant employment opportunities could arise during the construction phase, while job creation in operations and maintenance (O&M) may remain limited. Technologically advanced countries can develop indigenous capabilities and capture value locally in services (e.g. construction and project development) as well as in manufacturing (e.g. steel tubes for wind turbines and solar panels).

2. **Conversion into Power-to-X (PtX).** The transport and storage of hydrogen is costly, as it requires storage at either extremely high pressures or extremely low temperatures. The commercially viable alternative is to convert hydrogen into derivatives, such as ammonia, methanol or synthetic fuels, which are easier to store and transport. The choice of derivative depends on the specific end use (e.g. ammonia for fertilizer production and e-kerosene as aviation fuel) and transportation requirements. Producing sustainable fuels from GH2 in combination with an organic carbon source, such as dedicated energy crops or agricultural residues, creates a link between the energy and agriculture sectors and can thereby generate further employment opportunities (WWF et al., 2019).

3. **Export of GH2 and PtX.** Exporting hydrogen and its derivatives presents a significant opportunity for countries to enhance their foreign exchange earnings and generate tax revenues. By tapping into international energy markets, countries can attract foreign investment that exceeds the amount needed to decarbonize their local industry and transport sector. Exporting countries' mode of transport varies depending on their proximity to major import markets: those in close proximity can export hydrogen through pipelines, while those located beyond the 3,000 km pipeline distance have to rely on maritime shipping as their only option. In that case, jumpstarting the export economy with PtX, such as ammonia or methanol, will likely be a more cost-effective choice compared to molecular hydrogen, as the transport of GH2 in the form of liquid hydrogen or liquid organic hydrogen carriers (LOHC) significantly increases the total costs. The choice of exported commodities has a direct impact on the potential for local economic spillovers.

4. **Manufacturing of renewable energy equipment.** The core activities around green hydrogen production involve backward linkages to upstream suppliers of clean energy technologies, for example solar PV (e.g. solar cells, modules, and steel frames); wind energy (e.g. towers, blades and gearboxes); geothermal (e.g. turbines, pumps, condensers); and electrolysers (e.g. electrodes, electrolyte materials, membranes and stacks). Moreover, energy projects require storage solutions. Yet the supply market for both wind and solar energy has high barriers to entry: the solar PV wafer manufacturing capacity, for example is highly concentrated in China, which accounted for 97 per cent of global capacity in 2021. The remaining capacity is mainly located in the Asia-Pacific region (the Republic of Korea, Malaysia, Viet Nam and Thailand) (IEA, 2022a). Although market dispersion of wind energy is higher, China leads in wind turbine manufacturing, followed by Europe, the United States, India and Latin America (GWEC, 2021). The production of renewable energy technologies has a major impact on employment: China's solar PV value chain alone accounted for 1.6 million jobs in 2021, surpassing employment in construction and installation (1 million), and in the operation and maintenance of solar plants (0.8 million) (IRENA and ILO, 2022).

Figure 2.3. Activity clusters along the GH2 value chain



5. Decarbonization of domestic industries. Many local industries such as the chemical, iron and steel, cement, aviation, maritime and heavy cargo transport industries, can benefit from reengineering their operations by using GH2. Incentives to use GH2 in these hard-to-abate industries—either as feedstock or as an energy source—are buttressed by national decarbonization goals, corporate standards enforced by leading enterprises in global supply chains, and international trade regulations such as the EU's Carbon Border Adjustment Mechanism (CBAM). A shift towards GH2 is particularly relevant for economies with robust heavy industries, especially if they export to markets with high decarbonization standards. Additionally, countries with a significant mining sector can greatly reduce their carbon footprint by adopting GH2 to align their energy-intensive operations and exports to markets with stringent decarbonization requirements.

6. **Decarbonization of transport.** Transport is a major contributor to GHG emissions in many low- and lower middle-income countries, even surpassing industrial emissions. While battery-electric technology is the future for light vehicles, other segments such as long-range buses and heavy cargo transport may benefit from fuel cells or hydrogen internal combustion engines as potential alternatives. However, the transition from diesel to low- or zero-emission vehicles requires costly adjustments in the existing bus and truck industries. Despite these challenges, there are viable pathways to align decarbonization efforts with local economic value. Countries with large markets and diversified industries have a competitive advantage in developing low-carbon transport technologies as, for example in the case of urban rail technologies in China and India, and fuel-cell mining haul trucks in Chile and South Africa. Another viable pathway, which may also be suitable for smaller economies, is retrofitting traditional vehicles such as diesel buses with low-carbon engines (e.g. battery-electric, fuel cell or direct combustion).

7. **Attracting FDI in energy-intensive industries – renewables pull**. Many industries are aiming to decarbonize their global value chains over the next two decades. In countries with limited renewable energy and GH2 resources, there is a growing incentive to import energy-intensive parts and components such as aluminium, carbon-fibre parts, green steel and energy-intensive chemicals from countries with abundant renewable low-carbon energy sources. As pressure to decarbonize material consumption increases, as carbon prices rise and renewable energy and GH2 capacity are ramped up, relocations of energy-intensive processes are expected to rise significantly. This presents a promising opportunity for developing countries to embrace green industrialization and further advance their sustainability goals.

Box 2.2. The renewables pull effect

The "renewables pull" effect refers to the attraction of energy-intensive industries and investment in new industrial capacity in countries or regions with abundant renewable energy resources. This can lead to increased deployment of renewable energy, job creation and value added in these countries (Gielen et al., 2020). Industries that are likely to benefit from (at least partial) relocation in the future include steel and chemicals, as the long-distance transport of intermediate (e.g. DRI, ammonia, basic hydrocarbons) and (semi-)finished goods (e.g. steel, cast iron, urea, ethylene) to these industries will be cheaper than the costs of hydrogen transport. Verpoort et al. (2023) estimate relocation savings of around 20 per cent for imported steel and 50 per cent for urea and ethylene when there is a significant electricity price difference of EUR 50/MWh between the trade partners. This presents a win-win situation for trade partners, as projected for the case of steel: renewable-rich countries can export green iron instead of iron ore and H2 and its PtX, resulting in an increase in local employment of approximately 16 per cent and a rise in value added of 18 per cent. By shifting to DRI imports, renewable-scarce regions can outsource the energy-intensive processing of iron ore while preserving the final steps of steel production, strengthening their competitiveness in the green steel industry and protecting over 90 per cent of jobs (Agora Industry and Wuppertal Institute, 2023). The first commercial-scale steel factory based on GH2 is currently being built in northern Sweden, where electricity prices are extremely low and where there is an abundance of iron ore (H2 Green Steel). The rising cost of fossil fuels due to stricter climate policies or higher CO_2 prices, the reduced cost of renewable energy sources, for example through technological advances, subsidies, policy-induced incentives, as well as increasing demand for green materials and products (e.g. CBAM), will drive the renewables pull in the future. Other factors that will have an impact include the costs of transport, the availability of other essential inputs, and the relevance of domestic production (Samadi et al., 2023).

Table 2.3. Activity clusters related to GH2 production

Activity cluster	Employment effects	Aspects to consider	Country examples
Renewable energy generation and electrolysis	Significant during construction but weak in plant operation (depending also on type of RE employed)	• Engaging in core activities requires substantial capital and scale. In most developing countries, FDI and imported technologies are expected to play a leading role. • If not addressed early on, conflicts related to land and water use, and equitable access to clean energy may arise.	• To meet export demand of 10 million metric tonnes by 2030, Namibia intends to build local EPC companies.
Conversion into PtX	Significant during construction but weak in plant operation	• Capital- and scale-intensive, thus deterring new entrants. Core technologies are not mature (e.g. direct air capture). FDI and imported technologies are likely to play a leading role in most developing countries.	• By 2025, Chile aims to prioritize the deployment of GH2 in ammonia production for domestic use.
Export of GH2 and PtX	Substantial during the construction phase, but the potential for forward and backward linkages and technological learning is fairly limited	• High investments in ports, pipelines and storage capacities, as well as transport mode-specific investments (for ammonia synthesis, generation of LOHC and deep-freezing hydrogen). • Most potential exporting countries will strongly depend on imports of industrial equipment, which may considerably reduce net export revenues. • Tax exemptions are often granted to investors (which are typically permitted to operate in special economic zones), thereby reducing the host country's tax benefits.	• Namibia will prioritize the export of hydrogen derivatives including ammonia, methanol, synthetic kerosene and hot-briquetted iron using iron ore from Brazil or South Africa. • Uruguay plans to develop a port solution for synfuels export in Montevideo by 2025.
Mfr. Of renewable energy equipment	Strong employment effects	• High market concentration (especially of solar PV). • Hydrogen technology patents (electrolysers and fuel cells). • Some inputs are more accessible for local production (e.g. steel structures, wind towers, pumps, cables), while others such as PV cells, wind turbine components and blades are often technology-intensive and rely on imports (IEA, 2022d; Global Wind Energy Council, 2022).	• China is promoting the development of proton exchange membrane fuel cells. • Namibia intends to construct and deliver local component manufacturing for GH2 production. • Türkiye has well-established manufacturing industries for solar and wind energy components and plans to develop GH2 technologies.
Decarbonization of domestic industries	Strong employment effects	• High switching/start-up costs for clean technologies. Large subsidies for incumbent competitors. • It may be difficult to attract domestic customers due to initial price differentials between conventionally produced and "green" products.	• In Kenya, three fertilizer projects are currently being developed. • India supports GH2 production to enhance low-carbon steel production capacity.

Decarbonization of mobility industries	Strong employment effects	• Many emerging economies have established the domestic production of diesel vehicles, driving up the costs of the shift to electric and fuel cell technologies. • Lithium batteries and fuel cells are often not produced locally, resulting in most developing countries relying on imported low-carbon transport solutions such as battery-electric buses, trucks and urban rail systems.	• In Chile, researchers are developing a stationary prototype of a fuel cell mining truck to be placed on site at the Antofagasta PLC's Centinela copper mine. • The Shipping Corporation of India (or its potential successor, a private entity) will retrofit at least two ships to run on GH2 or other e-fuels by 2027. • China is promoting R&D of large hydrogen energy aircraft and is actively exploring fuel cell applications in ships, for example.
Attraction of FDI in energy-intensive industries	Strong employment effects	• Comparatively high capital costs (due to political, regulatory and market risks) of industry relocation dampen the renewables pull effect.	• The Brazilian mining company Vale and the Swedish start-up H2 Green Steel signed an agreement to study the development of green industrial hubs in Brazil, using iron ore briquettes produced by Vale as input material for green steel production. • ArcelorMittal concluded an MoU with SNIM to assess the feasibility of jointly developing a pelletization plant and DRI plant in Mauritania.

2.4. Building the GH2 value chain

The opportunities discussed in Chapter 2.3 can be simultaneously leveraged to create value. The socioeconomic impacts may vary significantly across different activity clusters. While large-scale export projects can improve the balance of payments, they might not stimulate industrial capabilities as much as projects focused on industry decarbonization or R&D investments in new GH2 technologies. The realization of these opportunities largely depends on contextual factors (see Figure 2.4) such as natural resources, the policy framework and institutions, level of technology and an enabling social and economic environment.

Technological knowledge. The GH2 value chain encompasses various technologies that are used in production, conversion, storage and in applications across industry, transport, buildings and variable renewable energy (VRE) integration, with many of these exhibiting low to medium maturity levels. Patent activities in hydrogen production technologies are dominated by European, the United States and Japanese applicants (IEA and EPO, 2023). A similar trend is observed for technologies related to hydrogen storage, distribution, transformation and applications, with between 84 per cent and 90 per cent of patent activity taking place in industrial countries in the Global North and China. Developing countries may face challenges entering this highly concentrated market, given the ambitions of major importing countries (Germany, Japan and the Republic of Korea) in hydrogen technology development. However, some countries may be able to leverage their expertise in related technologies, such as Fischer-Tropsch-Synthesis for synthetic fuel production (South Africa) or biofuel production (Brazil), giving them a competitive advantage in international markets.

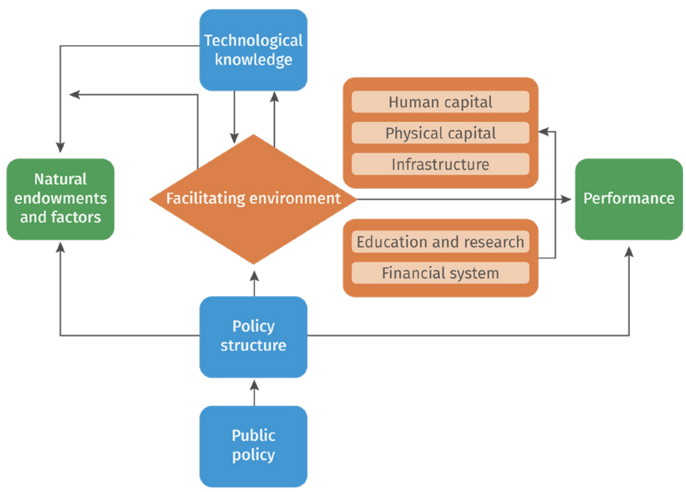
Natural endowment and locational factors. GH2 production heavily hinges on natural endowments. Factors such as solar irradiation and wind speed are key determinants of low-cost hydrogen production, as electricity costs account for 90 per cent of overall hydrogen production costs. Countries with abundant renewable energy resources and access to water sources have a significant advantage in terms of producing low-cost GH2. Water availability and quality are crucial for both hydrogen production and upstream processes such as cooling solar PV modules. Freshwater resources tend to have higher permeate rates compared to seawater (IRENA and Bluerisk, 2023), reducing the cost of GH2 production. Additionally, the availability of minerals such as silicon and copper for solar PV modules, rare earths for wind turbines, nickel for alkaline and solid oxide electrolyser cells (SOEC), and platinum group metals (PGM) for proton exchange membrane (PEM) electrolysers and fuel cells play a critical role in the production of hydrogen-related technologies. The domestic availability of iron ore is also advantageous for the production of DRI. Other locational factors include the presence of underground salt caverns for storing bulk amounts of gaseous hydrogen, as well as the proximity to import markets, as transport may increase the costs of hydrogen significantly.

Public policy and policy structure. Developing a robust GH2 value chain requires careful public policy considerations and public resource allocation to promising pathways and projects. To ensure a fair energy transition, it is crucial to implement strategies that incorporate mechanisms to share both benefits and risks based on realistic projections. The quality of policy structure is equally important and entails a range of important governance aspects. Political stability plays a pivotal role in attracting FDI for the development and expansion of clean energy technologies. Robust institutional capabilities facilitate coordination and cooperation between the public and private sector and the development and enforcement of appropriate standards. Additionally, strong public institutions promote transparency, accountability and the alignment of industrial policies with societal goals.

Facilitating the expansion of the GH2 market. The more diversified a country's economy is, the more effectively the linkage effects in both upstream and downstream GH2 production can be harnessed. Diversified economies can leverage their local capabilities for backward linkages, incorporating GH2 into existing downstream industries and preparing them for the low-carbon transition. Existing industry clusters, e.g. in the automotive industry, can accelerate the domestic expansion of the GH2 market. Air traffic hubs such as those in Qatar, Dubai, Abu Dhabi and Addis Ababa, offer opportunities to co-locate synthetic aviation fuel production. Infrastructure, including ports, rail, pipelines, etc., can be adapted to support GH2 production. Geostrategic assets, such as the Suez and Panama canals, provide opportunities for hydrogen storage and related services, as well as the co-location of downstream industries (Van De Graaf et al., 2020). Advanced technological capabilities embedded in firms and research institutions foster knowledge generation and technology indigenization. Countries that export oil and gas often possess transferable industrial capabilities that can be easily transferred to GH2 investments, e.g. in the production and operation of refineries and other chemical plants, as well as pipelines and storage facilities. South Africa has accumulated technological capabilities in coal liquefaction based on the Fischer-Tropsch process, which includes the handling and processing of hydrogen and the conversion of power-to-liquid. A transparent financial system, stable banks and favourable investment conditions, such as availability of risk capital, market liberalization and trade openness, also facilitate the integration of GH2 into the domestic economy.

Previous industrial development trajectories demonstrate the advantages associated with investing in socioeconomic endowments compared to relying exclusively on factor-cost advantages (Neary, 2003). Greater diversification and economic complexity unlock a multitude of new economic opportunities through a recombination of existing assets and capabilities. This, in turn, accelerates dynamic knowledge spillovers (Hidalgo et al., 2018; Hidalgo and Hausmann, 2009). It is thus essential for countries with factor-cost advantages in GH2 to avoid the formation of energy enclaves and to instead prioritize investments in domestic linkages, technological learning and support for institutions.

Figure 2.4. **Contextual factors shaping the development of large technical systems such as GH2**



Source: Adapted from Lipsey et al. (2005), p. 56.

Box 2.3. Just Transition

An inclusive and sustainable rollout of GH2 production must build on (i) civil society, by ensuring equitable access to GH2 technologies and community involvement in decision-making; (ii) skilled workforce, by investing in education and training and by supporting workers to transition from fossil fuel industries; (iii) productivity and innovation, by attracting investments to sustainable projects and the development of GH2 technologies; and (iv) the environment, by addressing potential environmental injustices linked to GH2 production.

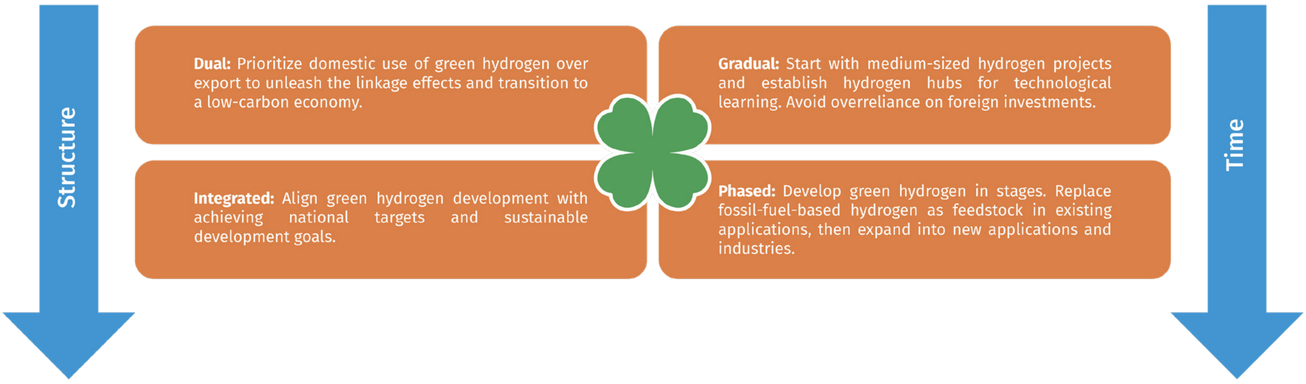
A Just Transition further implies a broad and equitable distribution of benefits from hydrogen production across society. The capital- and technology-intensive nature of GH2 production presents challenges in terms of generating direct employment and community-level benefits. In countries with low industrial and technological capabilities, the potential for linkage effects may be limited. While large-scale export projects can improve the balance of payment, they may only stimulate limited industrial capabilities and may have unintended consequences such as the Dutch disease effect, windfall gains for real estate investors, and rent-seeking behaviour among stakeholders. Governments should introduce benefit-sharing mechanisms and develop clear and transparent guidelines in a participatory manner to ensure a fair distribution of the gains from hydrogen investments (see Section 3.3.3).

2.5. The clover approach to GH2 development

By refocusing their efforts, developing countries can identify and leverage the specific advantages they stand to gain from entering the GH2 market. The advantages may include economic decarbonization, sustainable growth, technological advancement, and the creation of new employment opportunities. Many developing countries have already recognized the potential of these advantages and have incorporated them into their NHS. NHS must be seamlessly integrated into existing policy frameworks and address the uncertainties related to GH2 trade. This strategy plays a pivotal role in reducing risks and promoting the stability of the GH2 sector in production countries. In this context, initiatives need to be developed along two important dimensions: (i) the *structural dimension*, which determines the GH2 sector's contribution to sustainable development in these countries, and (ii) *the time dimension*, which outlines the phased roll-out of the GH2 sector over time.

Four key aspects that many developing countries have already included in their NHS emerge:

Figure 2.5. The clover approach to the GH2 market (illustration by authors)



Dual: Export and local use. GH2 and PtX exports may have substantive spillovers, e.g. when inputs are sourced locally. Such projects are often associated with conditions that do not encourage local linkages. Domestic value creation, industrial linkages, technological learning and permanent employment are more likely to be achieved when GH2 is produced for local uses, i.e. for decarbonizing the domestic economy and for promoting green industrialization.

Integrated: Alignment with other development targets. Successful GH2 development hinges on close alignment with broader national goals. Countries must therefore have a clear vision of how GH2 can contribute to the clean energy transition, to the achievement of the SDGs and the establishment of a resilient economy. Investing in renewable energy and grid infrastructure is a "no-regret" option, benefitting local industries and communities while also creating favourable conditions for the hydrogen industry's growth. **Creating leverage through regional cooperation**. Promoting regional cooperation can be particularly advantageous for smaller countries, e.g. through the development of joint education and training programmes and collaboration opportunities to develop high-quality infrastructure, thereby streamlining the implementation of the GH2 industry.

Gradual: Promoting the implementation of small- to medium-sized projects of hydrogen production and local offtake, despite the strong economies of scale offered by GH2 production. Pilot and demonstration projects enable learning-by-doing and learning-by-interacting, especially when accompanied by R&D investments and international knowledge transfers. Innovations in small-scale ammonia production show promise in enabling local green fertilizer production, even for small-holder agriculture (Brown, 2018; Kizuna, 2023). On-site ammonia production in rural communities can lower costs and emissions, enhance food security by reducing import dependencies and benefit remote areas (e.g. Vrijenhoef, 2017). When supporting large-scale export projects, preventing the creation of enclaves with their respective political and socio-economic risks is crucial.

Phased: Planning the production and application of GH2 in steps

1. **Existing green applications.** Matching the GH2 supply with demand, especially in the early stages of market formation, is particularly challenging. One effective approach is to leverage existing infrastructure, incorporate GH2 into current infrastructure systems without the need to retrofit and use incumbent processes. This strategy can accelerate market ramp-up (Cordonnier and Saygin, 2022). Industries that rely on fossil fuel-based hydrogen as feedstock can gradually transition to greener processes by substituting a growing share of their "grey" hydrogen with GH2.

2. **Capitalize on emerging market opportunities**. Countries with major airport hubs or large container ports should consider engaging in the production of synthetic jet and maritime fuel as an entry point into the hydrogen market. Countries that rely on ammonia or fertilizer imports can significantly reduce their exposure to international price shocks and save foreign currency by engaging in the production of green ammonia.

3. **Promote green industrialization.** The strong population growth projected in many developing countries, especially in Africa, and the urban migration trends will increase demand for basic materials such as iron, steel and cement. According to the IEA, demand for these industrial products will increase by 50 per cent between 2020 and 2030 (IEA, 2022b). Countries in the Global South can benefit from building up a green heavy industry and avoiding carbon-based stranded assets, reducing their dependence on system-relevant material imports and exploiting their early-mover potential in the international trade of green commodities.

3. Backward linkages in GH2 production

Upscaling GH2 production to 491 Mt in line with IRENA's 1.5°C scenario (IRENA, 2023c) is linked to significant challenges. This is particularly true for countries in the Global South, where substantial changes will be necessary to address the inadequate infrastructure, the lack of regulatory frameworks and financial incentives, as well as the need to bolster skills development and policymaking experience. These changes need to be implemented at a much faster pace and on an unprecedented scale, with investments matching national gross domestic product (GDP) (see Box 3.1.). Developing countries that aim to become leaders in GH2 production must be prepared to substantially increase their renewable energy capacity relative to their current power systems (see Box 3.2.)

Box 3.1. Namibia

Nearly half of Namibia's population is employed in agriculture. The initiatives outlined in the country's NHS are almost on par with the nation's GDP. The lighthouse project Hyphen Hydrogen Energy has secured a 40-year concession for a vast land area of over 4,000 km², with a projected investment of USD 9.4 billion in a green hydrogen venture. To put this into perspective, Namibia's GDP in 2021 was USD 12.2 billion. The government expects the successful implementation of these bold plans to result in the creation of about 185,000 direct and indirect jobs.

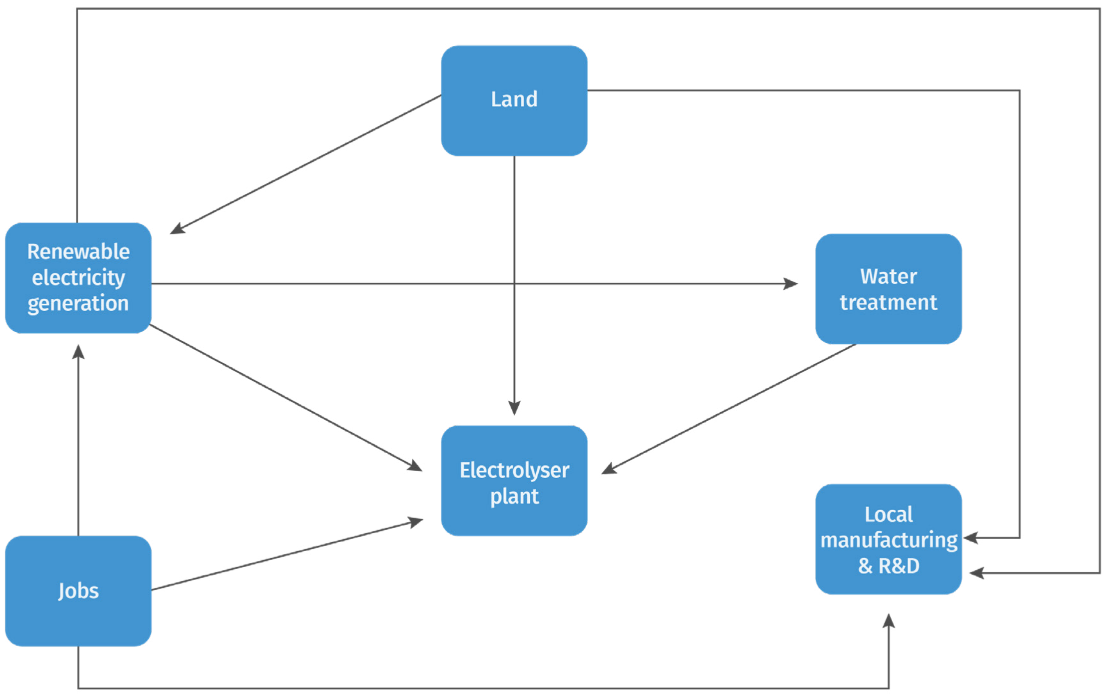
Box 3.2. Trinidad and Tobago

Trinidad and Tobago, one of the few Caribbean countries with a developed industrial sector and classified as a high-income economy according to the World Bank, currently produces around 2.5 Mt of grey hydrogen for its thriving chemical industry. The national hydrogen roadmap views this as an opportunity to gradually enter the hydrogen market, with the goal of producing 4 million tonnes of GH2 annually by 2065. This will require the installation of 57 GW of offshore wind power plants. To put this into perspective, the installed capacity of all power plants in the country in 2021 was nearly 20 times lower (about 3 GW, mostly natural gas-fired).

Experience in producing grey hydrogen is not necessarily useful for scaling up GH2 production because the technologies needed are inherently different (in terms of input requirements). GH2 production necessitates the development of dedicated infrastructure for the delivery of electricity and water to electrolysers; land availability; specific skill sets, and potentially even the local manufacturing of electrolyser components (see Figure 3.1.).

Policymakers must therefore focus on attracting investments to accelerate the deployment of renewable energy sources, develop strategies to supply renewable electricity for GH2 production, facilitate the acquisition of necessary technology imports, encouraging the growth of renewable energy technology and equipment in the manufacturing sector, and create an enabling environment for upstream supply chain development. Establishing and maintaining social contracts throughout these efforts is imperative.

Figure 3.1. Prerequisites for GH2 production projects



3.1. Strategies for attracting investors to GH2 production

Most countries in the Global South have limited financial stimulus measures to support the deployment of electrolysers. Instead of relying on supporting policies, they often adopt an "open to business" approach, with local policymakers focusing on addressing country risk factors to attract foreign investors rather than providing subsidies (Craen, 2023). Foreign enterprises sponsored over 70 per cent of all renewable energy generation projects in developing and transition economies in 2019, a number that is even higher in some developing countries (World Bank and Energy Charter Secretariat, 2023). Investors face three major risks: (i) technological, (ii) political, and (iii) commercial.

- *Technological* risks are associated with the quality of engineering and the reliability of the equipment being used.
- *Political* risks can materialize in the event of unexpected changes to the regulatory framework during the project's lifespan.
- *Commercial* risks refer to the uncertainty of long-term off-take agreements and prices.

These risks have real-world consequences. For example, although techno-economic analysis suggests that Egypt and Libya have the potential to supply significant amounts of hydrogen to Europe, their socio-economic potential is comparatively low, particularly relative to most European countries. Such elevated risks imply higher financing costs and a reduced likelihood of successfully implementing large-scale hydrogen projects (Braun et al., 2023). While investors bear primary responsibility for managing technological risks, both political and commercial risks are typically covered in regulations. The World Bank identified 119 arbitration disputes between investors and governments involving renewable energy projects initiated before 1 February 2022 (since 1998). The most prevalent political risk in such disputes are adverse regulatory changes (World Bank and Energy Charter Secretariat, 2023). Given its control over regulation and governance, the public sector plays a critical role in mitigating risks for international investors, especially in countries with low investment ratings or where concerns about information asymmetry might arise (IRENA, 2023a; World Bank and Energy Charter Secretariat, 2023).

To ensure a successful green transition, governments must develop an ambitious long-term vision for their renewable energy sector. This vision should include specific targets for capacity expansion and emissions reduction that span several decades. **In a first step, governments should identify short-term targets (5 years), medium-term targets (10–15 years) and long-term targets (around 20 years and beyond) for renewable energy and for both the energy and industrial sectors.** Strategic planning provides a clear roadmap for progress and facilitates effective implementation of renewable energy policies. To mitigate risks and attract investors, policymakers must prioritize the establishment of a long-term and transparent regulatory framework. This can be achieved by implementing measures that are widely adopted (see Chapter 4).

In the context of GH2 production, a long-term vision necessitates the development of a comprehensive NHS, which should contain clear guidelines for the hydrogen value chain's development, an overarching framework for future regulations, defined roles for government bodies and future support measures. The key objectives include establishing **the most conducive environment with clearly defined long-term regulations** that align with international standards. These include:

- Development of a NHS and establishment of national hydrogen governance regulations.
- Establishment of a framework for long-term land allocation based on leasing mechanisms, which is particularly important for locating renewable energy sources required for electrolysis.
- Development of a technical standards system and regulatory framework for implementing large-scale investment projects, aligned with international standards and practices (including permitting procedures, data access, etc.).
- Introduction of national hydrogen regulations as an energy carrier, which necessitates not only an alignment with existing international standards such as International Organization for Standardization/International Electrotechnical Commission (ISO/IEC), but also active participation in the development of new standards.
- Creation of a national green financing system (taxonomies) aligned with international standards on GH2 production.
- Alignment of the national hydrogen production certification system for carbon footprints with international practices; given the absence of universally recognized standards, consultations will be necessary to determine the optimal approach.

- For electrolysers, a **detailed regulatory framework for implementing hydrogen projects is necessary**. This includes the development of specialized regulations for hydrogen valleys (regulatory sandboxes), policies on local content (both for establishing assets for green hydrogen production and for O&M), and implementing R&D and educational programmes.

The establishment of a one-stop shop holds significant promise in bolstering a region's appeal for FDI. The concept of a one-stop-shop aims to streamline processes for potential investors by consolidating information, permits and services in a single location or website. By eliminating the need to navigate multiple channels, a one-stop-shop reduces bureaucratic hurdles/ red tape and saves time. Moreover, it provides comprehensive assistance to investors, covering a wide range of services, such as helping investors meet regulatory requirements, providing access to financial resources, and identifying local partners and suppliers. By offering readily accessible and clear information to investors, it builds trust and confidence in the investment process. Such transparency creates an environment that is conducive to investments and minimizes the potential for miscommunication or misunderstandings. One notable example of a successful one-stop-shop is Namibia's IAO (see Box 3.3).

Investments in renewable energy can be facilitated by establishing **a transparent and competitive framework for renewable electricity generation that attracts investors to new projects**. The traditional form of remuneration for such projects is through long-term power purchase agreements (PPAs) that offer investors stable cash flow and minimize country-specific risks. PPAs are typically concluded following open and transparent auctions, ensuring a high level of competition and continuous price reductions.

Renewable energy projects typically require high initial capital expenditure (CAPEX) and have minimal operating expenses (OPEX) across the project's lifespan. As a result, the weighted average cost of capital (WACC) plays a significant role in determining the feasibility of such projects. The CoC for utility-scale solar PV and onshore wind projects between 2019 and 2021 ranged from 3 per cent to 4 per cent in China, and from 10 per cent to 11 per cent in Egypt and Tunisia, respectively (IRENA, 2023b). Pioneering projects may often entail additional cost factors, such as underdeveloped local supply chains, logistics and regulatory frameworks. These challenges can be addressed through cost-effective instruments such as feed-in tariffs or tax incentives, as well as through the establishment of a dedicated government body, such as a one-stop-shop (see Box 3.3).

Box 3.3. Namibia's Implementation Authority Office

The Implementation Authority Office (IAO) plays a crucial role in supporting the implementation of Namibia's hydrogen strategy. It is responsible for overseeing hydrogen projects that are implemented on state-owned land, including the management of land auctions, regulatory reviews, permitting and financing. It engages with developers, contractors and investors, fostering strong relationships with the private sector and overseeing project contracts. As a one-stop-shop, it provides the necessary resources and consultations to streamline investment processes. The government aims to establish a special economic zone (SEZ) with favourable conditions for private sector-led development. Any obstacles that arise are promptly addressed, including negotiations with license owners to secure land. Careful project sequencing is implemented to minimize risks and maintain transparency (Ministry of Mines and Energy Namibia, 2022).

Due to the significant cost reductions in solar and wind energy production achieved over the past 15 years, renewable electricity has become the most affordable alternative to fossil fuels in most countries. As a result, the level and duration of subsidies now required by countries from the Global South embarking on a renewable energy development trajectory will be significantly lower than those in Global North countries at the beginning of the century. To increase the generation of renewable electricity, regulators can consider establishing a **dedicated hydrogen fund**, which can be used to implement financial stimulus measures, such as **tax incentives**, including reduced corporate income tax, equipment import tax waivers and value added tax (VAT) exemptions. **Accelerated depreciation** can also be offered to provide short-term financial relief and make GH2 projects more attractive to investors seeking faster returns. Additionally, **low-interest loans** and **national green bonds** set to tap into additional funding sources and to raise foreign capital for GH2 projects can be introduced, with the government's clear commitment to sustainability, as well as **exclusive government funding rounds**, reserved for GH2 projects within the fund's mandate (see Chapter 4).

Finally, **international cooperation mechanisms should be leveraged** to foster collaboration and facilitate GH2 projects between countries. With over 40 intergovernmental agreements on hydrogen trade globally as of May 2023, there is a strong foundation to involve governments, businesses and academia from different nations in joint project implementation. The strengthening of relationships with key stakeholders in the global hydrogen market should be prioritized as well, including hydrogen-importing countries, technology suppliers, international development banks and regional hydrogen associations.

3.2. Sustainable procurement of electricity for electrolysers

Renewable electricity plays a crucial role in GH2 production, with approximately 20 GW required for every 1 Mtpa GH2 produced. Most countries determined their national renewable energy targets between 2000 and 2010s, without considering the energy needs for GH2 production. It was only after 2020 that GH2 started gaining traction as an energy carrier in national strategies. To promote transparency and facilitate the deployment of additional renewable energy, countries have two options: either (i) revise their targets to incorporate electrolysers' energy requirements, or (ii) exclude the electricity consumed by electrolysers from their current targets (IRENA, 2021).

GH2 production should not divert investments from and overshadow the decarbonization efforts in other industries such as the power, transport and heating and cooling industries (the latter benefitting from electrification). Countries with a high share of renewable energy in their power generation, such as Uruguay or Brazil, have an advantage in GH2 production due to their experience in renewable energy technologies and a supportive enabling and regulatory environment. A decarbonized grid can provide clean electricity around the clock, increasing electrolysers' output. Moreover, **certification systems can ensure that sustainable electricity is consumed by grid-connected electrolysers**.

Export-oriented GH2 production projects in the Global South will be impacted by the additionality requirements adopted by importing markets, such as the EU, which is one of the two major regions for future hydrogen imports. Additionality—which was initially introduced in the EU—mandates that the electricity used in the production of hydrogen must come from renewable sources that would have otherwise not been generated. This measure aims to ensure that GH2 production does not displace the use of green electricity, which might result in existing green electricity users resorting back to fossil fuel-based electricity, consequently contributing to an overall increase in GHG emissions.

Additionality is primarily an economic and political constraint rather than an engineering constraint. **Countries in the Global South can adopt distinct additionality principles tailored to their own hydrogen consumption levels**. This allows for more relaxed requirements if the hydrogen is intended for domestic use rather than for export. Policymakers should be cautious when imposing stringent additionality requirements, as it may hinder a rapid deployment of hydrogen production for achieving economies of scale. This potential conflict may arise because strict additionality criteria can introduce complexities and increase project costs. A comprehensive hydrogen certification and tracking system should therefore be introduced, which, however, can be quite resource-intensive. Nevertheless, such measures are crucial to ensure that hydrogen projects are genuinely environmentally sustainable rather than to simply appear to be "green" on the surface, especially if policymakers have ambitions to export hydrogen or its derivatives to the EU, where stringent environmental standards apply.

It is worth noting that there is currently no globally agreed approach to establishing additionality requirements in GH2 production. Countries such as Australia, China, Japan, the United Kingdom and the United States have adopted approaches that differ from the EU's. For example, Australia and Japan do not set a maximum emissions threshold for certifying low-carbon hydrogen, while specific requirements for the additionality of electricity for electrolysers have not yet been introduced in Australia, China, the United Kingdom and the United States (IRENA and RMI, 2023). Applying a uniform additionality concept to all countries may not be practical. Different regions face unique challenges such as grid constraints, power outages, limited access of local communities to electricity, and varying levels of compliance and monitoring capabilities. Adopting a nuanced approach that considers these factors is therefore far more beneficial.

It is worth exploring the possibility of countries in the Global South **engaging in negotiations with importing countries for more equitable trade conditions for GH2 and its derivatives**. As potential GH2 suppliers, hydrogen exporters should be given the opportunity to discuss and establish terms of trade that consider their unique contexts and requirements. This approach would promote fairness and bolster collaborative efforts in shaping the global hydrogen market, potentially leading to a more inclusive and sustainable energy transition that benefits all. At the same time, developing countries should prioritize investment in renewable energy to progressively decarbonize their power grids. They will thereby lay the foundation for future projects that can fully adhere to strict additionality criteria.

3.3. Technology acquisition and local manufacturing options

Access to technology is a crucial factor in the development of a GH2 industry. Reliance on new technologies may pose a challenge for countries in the Global South as such reliance may impede economic growth and hinder the transition towards a green economy. The current global technology supply chain for solar and wind energy as well as battery-based energy storage is heavily concentrated in China and to a much lesser degree in countries from the Global North. China also holds the largest share of global water electrolyser manufacturing capacity, accounting for approximately 40 per cent, while the EU and the United States hold 20 per cent each. There are plans to implement additional electrolyser manufacturing projects, which will lead to a more diversified regional distribution of electrolyser manufacturing capacity by 2030. By then, China and the EU are projected to hold 25 per cent of global manufacturing capacity each, while the United States will maintain its current share of 20 per cent (IEA, 2023c).

It remains uncertain whether the current concentration of core hydrogen technologies can be sustained in the long run. The manufacturing of hydrogen equipment requires natural resources, including critical minerals, and technologies to process them. The supply chain for hydrogen equipment is still in its early stages, with electrolyser manufacturing capacity currently 100 to 1,000 times smaller in scale than what is currently needed. To achieve economies of scale, it is crucial to use more cost-effective materials and automate electrolyser manufacturing plants. This will contribute to a reduction in dependency on materials such as PGMs and ensure a more sustainable and efficient production process.

As GH2 projects continue to expand, developing countries face the threat of becoming reliant on technologies and supply chains owned or controlled by other countries and foreign companies. This dependence may restrict their ability to engage in the production, operation and maintenance of these technologies, and thus limit their access to relevant knowledge and skills. Consequently, they may lack technological sovereignty and thus be unable to adapt or innovate in the future. While it may not be feasible for most countries to effectively compete in all steps of the supply chain, recent crises have brought to light the vulnerability of supply chains, O&M security and the costs of global events such as COVID-19 and regional conflicts. Policymakers must therefore strike a balance between these competing considerations. They can choose between two major scenarios, which allow for different risk management strategies and the realization of opportunities specific to the country.

3.3.1. Scenario 1: Local content requirement (LCR)

To enhance the local content in the creation of new electrolysis and renewable power plants, **mandatory and measurable requirements for the share of local content in equipment, labour and services** should be introduced. These requirements can represent a mandatory condition for participation in subsidy programmes or for eligibility for additional support.

Local content requirements (LCRs), i.e. a predefined minimum local content threshold, have been introduced as part of the eligibility requirements for developers to participate in renewable energy auctions. This has been the case in Brazil, Morocco, South Africa, Türkiye and the United Kingdom, among many others. The outcome has been mixed, depending on policy design, implementation and context. LCRs have been successful in South Africa's wind tower segment, for example, but have faced some challenges with turbine manufacturing, which is more technologically demanding (IRENA, 2019). LCRs can be gradually increased to encourage the use of local resources. Monitoring mechanisms can ensure investor compliance with these requirements. Additionally, incentives, such as long-term tax breaks and subsidies to facilitate the establishment of factories in the given country can be introduced to attract foreign vendors to partner with local investors.

In three countries from the Global South that implemented LCRs and that auctioned the highest renewables capacity up to 2019, namely Brazil, India and South Africa, developers gradually shifted towards roles that are more easily borrowed from other industries, such as project development or ancillary services. Establishing manufacturing capacity is more challenging, and any growth observed is primarily limited to less sophisticated components. Moreover, the implementation of LCRs may increase project costs. Simply establishing an LCR does not guarantee the creation of a competitive manufacturing sector. Instead, such restrictions create an artificially localized market, the volume and long-term development of which are subjective and entirely determined by the local regulator's decisions (e.g. in terms of subsidies) and the pace of national economic growth. These uncertainties may negatively impact the decisions of major developers to deploy corresponding manufacturing capacities in the country. Without guaranteed long-term sales and a global market for the produced goods, these investments become meaningless. As a result, a risk of manufacturing capacity shortage to meet the LCRs may arise. This, in turn, may lead to delays in the implementation of planned renewable energy projects and to increased costs due to the lack of competition in the market (Bazilian et al., 2020).

3.3.2. Scenario 2: Long-term stimulation of the country's own R&D

In this scenario, **multi-year strategic public investments in R&D are made to foster the growth of the research ecosystem and encourage an increase in the number of patents**. Regulators play a crucial role in creating a supportive investment environment for start-ups and facilitating the commercialization of technologies. One notable example in the context of hydrogen is South Africa, which launched the Hydrogen South Africa (HySA) research, development and innovation programme in the late 2000s.

Implementing this scenario in countries in the Global South is challenging due to the diverse nature of hydrogen technologies, which impacts multiple industries and scientific disciplines. The development and commercialization of such technologies require substantial investments and are associated with high risks. As of 2020, leaders in patenting hydrogen-related technologies had already emerged, with Europe accounting for 28 per cent, followed by Japan (24 per cent), and the United States (20 per cent), with the Republic of Korea and China on the leading countries' heels (IEA and EPO, 2023). Moreover, the successful development of green hydrogen production technologies is path-dependent on industrial preconditions and the presence of a number of related industries (principle of economic relatedness). Müller and Eichhammer (2023) produced a list of 36 "Green H2 Products" needed for stand-alone hydrogen production plants, which are comparatively complex to produce. Manufacturing these products could represent an opportunity for countries to achieve a green diversification of their manufacturing sector and avoid technology dependency. Possible policy instruments to achieve this include coordinating efforts with international partners to reduce supply chain risks, making joint investments in critical supply chain components; creating information platforms for clean technology manufacturing partnerships; sharing best practices for favourable investment conditions; promoting resource-efficient technologies; establishing sustainability standards, and facilitating participation of countries from the Global South in the GH2 supply chain.

Box 3.4. Local manufacturing and technology development: Cases from NHS

Namibia's hydrogen strategy aims to boost economic development by gradually increasing local content manufacturing. The local production of towers and blades and the localization of solar cell and module manufacturing could have a significant impact on the country's GDP, generating USD 11 billion by 2035–2040, and creating an additional 11,000 jobs annually. However, due to the complexity involved, the production of core electrolyser components is expected to remain overseas in the medium term. Nonetheless, balance of plant (BoP) and assembly facilities could be localized once domestic demand reaches a scale of 3-4 GW per year. Localizing the manufacturing of stacks (non-membrane) and BoP could generate USD 5 billion and create an additional 5,000 jobs by 2035–2040. Numerous opportunities for local manufacturing will also arise in the bioenergy industry for the production of biogenic CO_2. Namibia's hydrogen strategy involves the establishment of the Namibia Green Hydrogen Research Institute (NGHRI), which will conduct R&D, provide training and help localize the value chain. The NGHRI will serve as a science and technology park for university-industry-government consortia with a wide range of activities.

Colombia's NHS (Ministerio de Minas y Energía de Colombia, 2010) promotes the establishment of local industries to develop hydrogen technologies across the value chain. This includes companies involved in the manufacturing, assembly and installation of equipment, engineering firms, as well as firms engaged in component and equipment processing. Additionally, the government plans to support domestic R&D in low-carbon hydrogen by leveraging existing funds for science, technology and innovation. Through this policy, the regulator aims to bolster Colombia's domestic capacity and assess the possibility of creating a National Hydrogen Centre in the future to industrialize and export these technologies.

3.3.3. Just transition aspects of hydrogen production projects

The GH2 transition will have significant implications for energy, water and food security. Furthermore, impacts on land use, ecosystems and biodiversity must be anticipated. The challenge lies in minimizing negative externalities while ensuring that the resulting benefits and revenues resulting from GH2 adoption are shared across the entire country. In developing policy measures, it is important to note that GH2 production projects will be more sustainable and long-term if they are implemented in accordance with the principles of a just transition. Countries in the Global South often face multiple challenges in meeting citizens' basic needs, including access to electricity, clean water, employment, clean air in cities and education. When deploying large-scale GH2 production projects in these countries, it is essential to avoid exacerbating these issues and instead to contribute to addressing them in line with the SDGs. A replication of the practices of the oil, gas and mining industries, which often focus on opaque export-oriented projects reliant on natural resources, should be prevented. GH2 production projects should serve as catalysts for green industrialization, and promote an equitable distribution of benefits. This can be achieved by providing access to renewable electricity and water supply, stimulating local industry and fostering education and R&D (Altenburg et al., 2023).

Energy access and security

In many potential GH2-producing countries, a significant share of the population still lacks access to the electricity grid and/or relies on fossil fuels for their energy needs. This is the case in many African countries in particular. Consequently, a transition towards a GH2 market presents a unique opportunity to address these issues by simultaneously enhancing both local energy access and security while accelerating decarbonization efforts based on expanding renewable energy sources to ensure universal energy provision – any surplus clean energy can be employed for GH2 production. To achieve this goal, voluntary energy compacts and corporate social responsibility (CSR) initiatives can play a key role in realizing clean and affordable energy for all (SDG 7).

Water security

GH2 is produced through the process of electrolysis, which splits water into oxygen and hydrogen using renewable energy. While water is a principal input for GH2 production, it is important to consider overall water consumption. Under IRENA's 1.5°C scenario, GH2 production would consume around 12 billion m^3 of water annually (IRENA and Bluerisk, 2023). Although this number may seem daunting, it is only a fraction of the water presently being consumed by other sectors. For example, agriculture alone consumes up to 2769 billion m^3 annually. It could nonetheless still pose challenges in regions already facing local water stress. Most areas with high solar potential are arid and are often affected by water scarcity – a problem that climate change will severely exacerbate in the future, particularly in African countries. While treating wastewater or desalinating seawater may provide additional freshwater resources, the latter requires substantial energy inputs. Striking a balance between the competing water needs of GH2 production and of communities already feeling the impacts of climate change is therefore crucial. Additionally, water use in local communities extends beyond drinking water consumption and includes agricultural needs, which directly impact food security.

Land use and food security

GH2 production, particularly if electrolysers are powered by solar energy, is usually quite land-intensive. For example, a 1 GW electrolyser requires around 2 GW of solar PV, which translates into an estimated 26 km^2 of land (assuming 75 MW per km^2). While advancements in technology can mitigate the land impact, it remains a critical concern. Land requirements may compete with agricultural activities, potentially affecting local food supply and food security. Other land conflicts related to displacement, property devaluation or environmental degradation may arise, impacting not only individual citizens but also industries such as tourism. On the one hand, the displacement of water and land use from agriculture to GH2 production may jeopardize food security. The establishment of a GH2 sector, on the other hand, can increase food security by providing a low-carbon input for fertilizer production (Bezdek, 2019; Mukelabai et al., 2023).

Inclusiveness and shared benefits

In light of the security concerns already outlined, it is crucial for governments to consider the resilience and livelihoods of local communities when planning the roll-out of GH2 production. While potential benefits such as employment opportunities and export revenues are important considerations, they should not come at the expense of energy, water or food security.

Public participation and the involvement of local communities are integral to the formulation of strategies to ensure that all stakeholders' voices are heard and that public perceptions of loss and injustice are considered (Upham et al., 2022). The management of a just industrial transition entails accepting and navigating trade-offs between different dimensions of justice, equity and participation rather than focusing on a predetermined "win" in all dimensions. Moreover, the different dimensions of sustainable energy development (environmental, social and economic) may conflict with one another (ibid.). For example, while an accelerated transition to renewable energy may result in more equitable electricity access for the population, it may also result in the unjust displacement of certain local communities from their farmland. To prevent the dominance of hegemonic actors or entrenched majority views in decision-making processes, it is crucial to give a voice to under-represented groups. Engaging women and youth, in particular, will be essential for a successful and inclusive GH2 transition. They are equally affected by its consequences and will increasingly contribute to the workforce that will drive this transition.

To ensure a fair distribution of the benefits from hydrogen investments, governments can thus adopt a participatory approach and develop clear guidelines. Some strategies in this context include:

- **Generating fiscal revenues by leasing public land or maritime areas to renewable energy projects**. The rent charged should relate to the difference between the project's levelized costs of energy (LCOE) or of hydrogen (LCOH), and the regional or global market's LCOE/LCOH, while also accounting for transport costs. This approach can be informed by existing economic literature on resource rent issues in extractive economies.

- **Reinforcing the reinvestment of profits in the host country** by imposing restrictions on excessive income repatriation and promoting benefit-sharing requirements, e.g. investors can be required to make community development investments if they want to participate;

- **Supporting citizen participation schemes for energy projects** such as energy cooperatives and other forms of "distributed ownership";

- **Earmarking fiscal revenues for broad-based or pro-poor spending**, e.g. for education and research or structural transformation of regions, especially those negatively affected by the transition to a low-carbon economy;

- **Using fiscal revenues for direct payments to citizens.** Examples of successful models include the Alaska Permanent Fund Dividend Scheme which pays an annual dividend from mineral royalties to all Alaskan residents, and Mongolia's resource-to-cash payment programme that uses coal-mining revenues to provide cash transfers to all citizens;

- **Saving fiscal revenues for future generations and/or long-term public investments**, e.g. the Norwegian Oil Fund.

Social contracts in the context of GH2 production projects primarily revolve around the welfare of local communities. They can vary depending on the specific context:

- In indigenous communities, social contracts may include revenue-sharing agreements, job opportunities for community members and investments in community development, such as improved housing and healthcare facilities.

- In developing countries with limited access to electricity, social contracts for a GH2 project may require developers to allocate a share of renewable energy production to local electricity consumption, ensuring cleaner and more reliable power for all.

- In regions with a high renewable energy potential, social contracts may involve training and employing local residents in the O&M of power plants, creating job opportunities and contributing to the local economy.

- In water-stressed areas, social contracts associated with GH2 plants may include agreements to support local agriculture through sustainable water management practices or desalination projects sized to provide water to the local population.

Projects may be technically and economically feasible, but without the establishment of social contracts, their overall success can be significantly impeded, highlighting the importance of addressing community concerns and fostering mutually beneficial relationships between project stakeholders and affected communities. The absence of social contracts in project development, including GH2 initiatives, can result in a host of detrimental outcomes. Communities may feel excluded and perceive a lack of transparency in decision-making processes, resulting in increased resistance and opposition to such projects. This resistance can manifest in protests, legal disputes and project delays, ultimately undermining the initiative's success. Additionally, the absence of social contracts may neglect important environmental considerations, potentially causing long-term harm to ecosystems and local environments, which can have far-reaching consequences for both the project and communities involved.

Other proposed measures to enhance community resilience and protect ecosystems include conducting integrated socio-environmental impact assessments, which can determine the true cost and feasibility of GH2-related infrastructure projects before construction commences. Pricing or regulatory interventions to internalize environmental externalities on a broad scale can achieve both a reduction of harmful impacts and enhance GH2 competitiveness by narrowing the price gap with other hydrogen production methods. CSR can play a significant role in ensuring a just and sustainable GH2 transition. Local, regional and international partnerships may also mitigate the security risks associated with GH2 production. Ultimately, achieving a GH2 sector that benefits both people and the planet will require the cooperation of all stakeholders, including government, the public and the private sector.

4. Local downstream market creation policies

Effective policy coordination is essential for creating local GH2 markets and establishing a comparative advantage in green industrial diversification. Without policy support, this process is likely to unfold extremely slowly, if at all. Policymakers should therefore prioritize policy interventions and policy instruments to facilitate the development of a localized GH2 value chain.

Developing countries with abundant renewable energy resources can produce GH2 competitively and leverage it for industrialization. **To reap the long-term benefits of the GH2 industry, establishing a localized GH2 value chain that includes downstream green industries as end- or intermediary users of locally produced GH2 is crucial.** This requires a shift towards green industrial diversification by encouraging existing and new industries to produce intermediary "green goods" such as green ammonia or green steel. This can also lead to the production of final end products (e.g. green fertilizers) or further intermediary green products (e.g. green car part manufacturing). Such green industrial diversification is associated with higher levels of employment and higher export potential for high-value green goods than the production and export of GH2 alone.

The local value chain has the potential of expanding its reach to various industries such as hard-to-abate industries including iron and steel; non-ferrous metals such as aluminium; chemicals such as ammonia for fertilizers, and petrochemicals; non-metallic minerals such as cement, and to mining, which can employ domestically produced GH2 either as a feedstock or as a combustion fuel. Apart from industrial applications, hydrogen can also be used in other industries such as PtX, energy storage, mobility and heating. GH2-based industrialization may also result in the establishment of local upstream manufacturing of electrolysers and renewable energy equipment (see Section 3.3.2). Where not specified otherwise, the policy options discussed in this chapter can be applied to any of the industrial sectors addressed in this report.

"Green goods" are products that are manufactured using processes, technologies or materials that have a reduced carbon footprint, i.e. products with a lower environmental impact than conventional alternatives. Green manufacturing plays a crucial role in efforts to decarbonize industries and to achieve the climate goals outlined in the nationally determined contributions (NDCs) to the Paris Agreement. In addition to addressing the environmental imperative, green goods also present major economic opportunities for developing countries. As these countries experience rising income levels and lose their comparative advantage in low-cost labour, they can leverage their lower renewable energy costs to develop a new comparative advantage in the production of green goods. This shift towards a green industry also enhances these economies' competitiveness in the global industrial market, especially in light of policies such as the EU's CBAM.

Sequencing regulatory measures over market creation phases and time can provide the necessary predictability for market participants and investments. The initial market creation phase ranges from technical readiness to multiple large-scale projects, as described in the clover approach (see Section 2.5). Whether these projects build on existing industries or expand into new ones depends on the starting point of the respective country's industrial structure and composition. As such, LDCs may have little to no existing industrial base, while more advanced and/or energy-producing economies from the Global South may already have a pre-established industrial base. The objective for policymakers in the market creation phase is thus to demonstrate the viability of full-scale commercial facilities and to cultivate a secure environment for project developers, investors and key value chain stakeholders to scale the market. This requires developing a comprehensive policy package with supporting measures. Over time, this policy package can be adapted to the market's evolution: from a gradual expansion of applications and project size along with cost reductions to eventually achieving a mature and competitive industry for products manufactured using GH2. Various policy options are introduced in the following sections to achieve the aforementioned objectives:

1. Ensuring regulatory alignment, transparency and long-term stability to mitigate risks for businesses and investors. Implementing a streamlined governance framework that offers a single point of contact for project developers.

2. Supporting early adopters operating in high-risk segments of the industry while providing targeted incentives to attract the necessary (foreign) financing for the value chain.

3. Stimulating commercial demand (both intermediary and final) by bridging the price gap as a supportive measure during the local value chain's take-off phase. Enforcing requirements for local content and employment to ensure local benefits.

4. Promoting integration, risk-sharing and skills development across various sectors and industries along the value chain can improve efficiency and increase investment attractiveness.

4.1. Regulatory clarity and stability

Countries embarking on a GH2-based industrialization trajectory must have a clear and long-term vision, as well as an acute awareness of potential technology disruptions. To fully capitalize on the opportunities presented by the GH2 industry, countries must assess the production, domestic consumption and export potential of GH2. This assessment serves as the foundation for setting government goals, developing strategies and ensuing adaptability to innovations and changes in the supply chain. Several factors need to be considered when designing policies for the GH2 industry. They include the country's capacity for renewable energy, its existing gas infrastructure, the feasibility of hydrogen transportation, and the availability of a skilled workforce. Local industry regulations also play an important role in shaping the GH2 industry. Crafting effective GH2 industrial strategies begins with defining the role of GH2 in future economic growth. This entails addressing challenges such as job creation, trade opportunities, supply chain risks and energy security. An integrated approach that aligns with the country's national goals and considers trade-offs is essential for maximizing the benefits of GH2.

In formulating a GH2 vision, policymakers should avoid a strictly "top-down" strategy and instead adopt a participatory approach involving both public and private stakeholders, which will help build trust and create a shared vision. For instance, the *PlataformaH2 Argentina* brings together actors from the public and private sectors and from civil society, and encourages corporate, industrial, trade union, academic, technical and scientific segments to be part of the debate on Argentina's GH2 policy. This inclusive approach provides direction for growth by guiding business expectations and activities in the GH2 value chain without dictating how to achieve success but instead empowering entrepreneurship: "It is not about levelling the playing field but about tilting it towards the desired goals" (Mazzucato and Kattel, 2023). The government's GH2 vision is consolidated in a public document such as a "roadmap" and clarifies the "w"-questions of hydrogen in a country: "why hydrogen", "where in the country", "when is it happening", and "which applications". By defining an integrated plan with the necessary activities to better assess hydrogen's potential (IRENA, 2020b), countries can effectively align their efforts in the GH2 industry (see Chapter 2.1 for additional information on country visions for the hydrogen industry).

Once a clear vision has been articulated, the adoption of an NHS or roadmap signals stability and provides a sense of strategic direction for all stakeholders involved. A long-term government strategy offers clear policy direction for the industry about future market conditions and targeted projects. The strategy should explicitly outline hydrogen targets across the value chain and define key performance indicators (KPIs) for advancing GH2 deployment. GH2 strategies should adopt a cross-sectoral approach and look beyond the boundaries of individual industries. The interactions between different industries must be considered as well to promote synergies and spillovers along the GH2 supply and value chain, and to address the cross-sectoral national development goals informing the government's GH2 vision. Due to the necessarily broad scope of the envisioned actions, it is crucial to firmly embed and align the GH2 strategy document with other existing strategies for industry, energy, FDI, skills development and innovation, as well as other relevant strategies.

Policymakers can operationalize the pursuit of long-term GH2 goals by breaking them down into manageable tasks and milestones. Adopting a mission-oriented policy approach that sets out one or several missions, i.e. compelling and ambitious tasks that provide direction and intention, may be very useful when transitioning to a new energy matrix. **Committing to concrete targets through policy action can be instrumental in bringing all GH2 stakeholders on board, ensuring that different industries' visions are aligned in scale and timing** (IRENA, 2020b). Translating these milestones into binding short-term targets significantly reduces policy risks for stakeholders and potential investors, offering them concrete provisions and numbers to work with. Short-term targets may include quantified CO_2 reduction targets, quotas and standards that incentivize GH2 adoption in end-use industries, paving the growth of GH2's ecosystem. The establishment of KPIs, such as the European Commission's recently proposed EU-wide 2030 target for a 50 per cent share of renewable hydrogen consumption in industry provides direction and market foresight to all stakeholders in the GH2 value chain (Hydrogen Council and McKinsey and Company, 2022).

Box 4.1. Example of GH2 strategy: Morocco

The Kingdom of Morocco launched a regional initiative to establish an economic and industrial sector centred on green hydrogen, ammonia and methanol. This initiative is driven by Morocco's commitment to energy transition, the reduction of GHG emissions, and support for partner countries in their decarbonization efforts. With an ambitious investment plan of around USD 9 billion (MAD 90 billion) by 2030 and about USD 76 billion (MAD 760 billion) by 2050, Morocco aims to drive the growth of its GH2 industry. The timeline for adopting GH2 in industry consists of three phases: 2020–2030, 2030–2040 and 2040–2050. In the short term, the focus is on using GH2 as a raw material in local industries such as fertilizer production, while also exploring opportunities to export hydrogen products to countries pursuing decarbonization. The medium-term objective involves driving down costs and establishing favourable environmental regulations to facilitate economically viable projects both at the domestic and international level. Morocco's long-term vision includes expanding the use of green hydrogen in sectors such as electricity storage, transportation, industry, residential heating and urban mobility. To achieve these ambitious goals, Morocco plans to establish a National Hydrogen Commission, develop technology, infrastructure and markets; implement favourable regulatory measures, and invest in research and innovation to enhance the competitiveness of national companies in the GH2 industry.

Policies that establish clear, long-term regulatory definitions and standards are essential for creating a favourable environment for investors in the GH2 industry. This not only applies to GH2 production, but also to green goods manufactured by end-user industries, such as green steel. Given that GH2 projects often span several decades, policy certainty is crucial to enhance long-term investment security and minimize the risk of stranded assets. Additionally, the regulatory framework can support downstream industries by developing green goods standards and certifications, public-private cooperation initiatives and guidelines for green public procurement (see Section 4.3). International standards, such as as those established under ISO Technical Committee 197 on hydrogen technologies, can be adopted to facilitate access to international markets of green goods and technology components needed for the construction of GH2 clusters (UNIDO, 2023a). Such standards may also serve as a foundation for developing local standards tailored to specific local contexts. Technical industrial process standardization increases operational safety and reduces technology risks.

The speed and prevalence of GH2 and the roll-out of green goods as well as the financial backing they are likely to receive are heavily influenced by the regulatory system's efficiency and transparency, and the ease of licensing and operating for industrial projects. Excessive regulatory barriers can hinder industrial development and the GH2 industry's growth. Such barriers can have a significant impact on the costs and risks of doing business, thus discouraging potential investors and entrepreneurs. Complex or inefficient provisions for property registration, tax codes, contract enforcement, availability and cost of loans, financial reserve requirements and insolvency resolution can significantly slow down project development. Simplifying government structures can enhance efficiency and transparency, as long as capacities are not compromised. Other factors to consider include legal protections for (minority) investors, corruption, availability of skilled labour (see Section 4.4), and the quality of infrastructure (see Chapter 5). Establishing and firmly imposing balanced regulations and permits that address valid interests can help avoid disputes between enterprises, communities and the government.

Reviewing and adjusting bureaucratic hurdles can effectively reduce costs and lead times for project development. Policymakers play a crucial role in establishing a stable and predictable environment that protects investors' interests and helps attract long-term investment for large-scale projects. The following measures should be considered:

1. Ensure business registration and licensing procedures are clear, logical and valid. If necessary, streamline the process to reduce bureaucracy and corruption;
2. Simplify tax codes to encourage investment and entrepreneurship;
3. Strengthen property rights and enforce contracts to provide businesses with greater certainty and security;
4. Establish effective dispute resolution mechanisms;
5. Create a transparent and predictable regulatory environment that fosters competition and prevents regulatory capture;
6. Invest in education and skills development to build human capital and increase productivity (see Section 4.4).

Permitting is a major bottleneck that hampers the GH2 value chain's development. The establishment of greenfield industrial development projects requires available land for construction. However, the lengthy and complex environmental grid management and other permitting processes often lead to significant delays or even hinder the construction of GH2 facilities and infrastructure (IEA, 2019). To address this issue, governments should aim to remove unnecessary red tape while ensuring that no corners are cut, which could undermine legitimacy and potentially lead to conflict. One approach to streamline and accelerate permitting procedures is the creation of one-stop-shops at both the local and national levels. These designated agencies or departments serve as a central point of contact for all permitting-related matters. Such centralization helps reduce administrative burdens and provides applicants with a clear and efficient channel to navigate the permitting procedure. Where multiple agencies are involved, interagency coordination becomes crucial to streamline permitting procedures. Establishing effective communication mechanisms helps prevent the duplication of efforts and reduces processing times. Additionally, the relevant authorities must have adequate capacities to manage all permit applications in a timely manner. Other options can be explored to further streamline permitting, such as:

- **Developing standardized permitting templates and forms**: this simplifies the permit application process. They should provide clear guidelines on the necessary information and documentation, making it easier for applicants to compile the required materials.

- **Implementing time-bound approvals**: governments can set specific timeframes for each stage of the permitting procedure to ensure that applications are reviewed and approved within a reasonable timeframe. Clear deadlines and accountability mechanisms help prevent unnecessary delays and ensure timely decision-making.

- **Providing online application systems**: Developing online platforms or portals for permit applications can significantly accelerate the permitting procedure. They allow applicants to submit their applications, track progress, and receive updates electronically, reducing paperwork and administrative burdens.

- **Offering expedited permitting options**: governments can introduce expedited or fast-track options for certain types of low-impact projects that meet specific criteria. These options prioritize projects that have minimal environmental or social impacts, allowing them to proceed more quickly.

4.2. Providing support for early movers

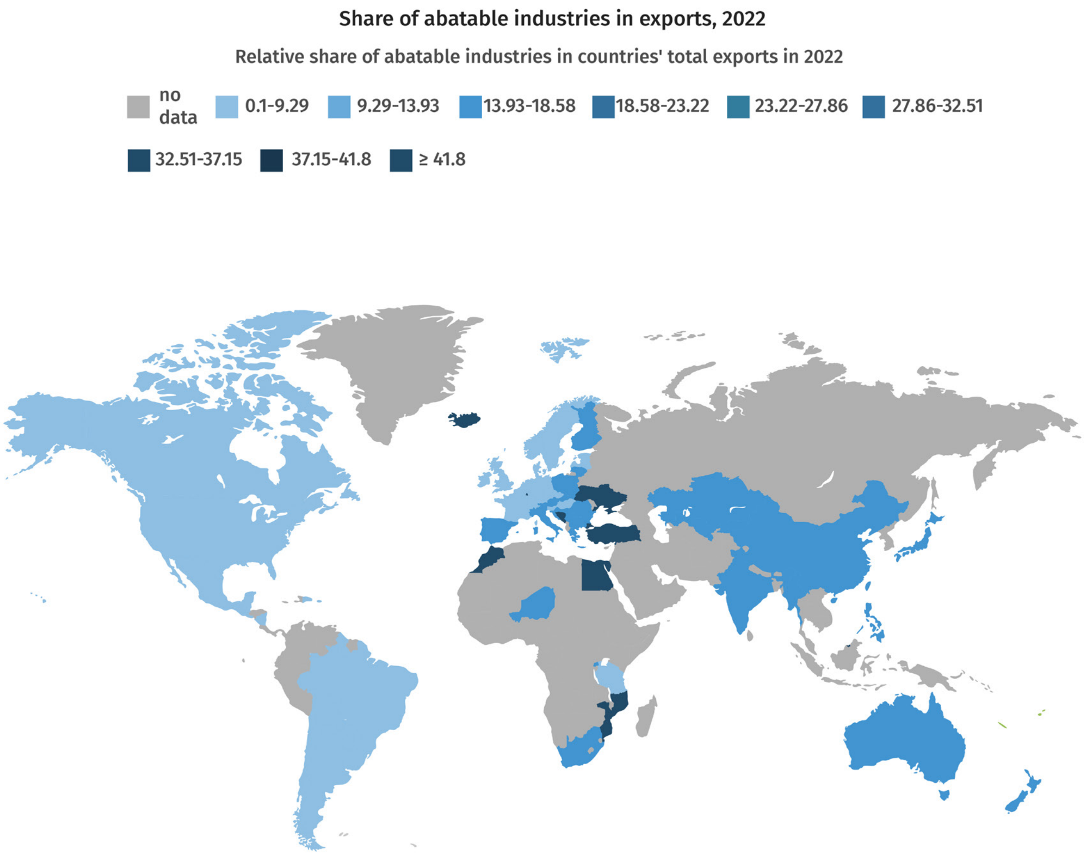
Some countries in renewable-rich regions such as Latin America, Northern and Southern Africa and the Middle East have a unique opportunity to **capitalize on their GH2 potential and become early movers in providing a range of decarbonized goods and services**. This includes engaging in low-carbon manufacturing in hard-to-abate industries, manufacturing equipment for electrolysers and GH2 infrastructure, mining and technology services. Supporting early mover projects will be key in establishing a strong presence in international export markets. The potential scope of a country's GH2 strategy and value chain will depend on whether it already hosts industries that can employ GH2 as feedstock or fuel. If that is the case, such facilities should serve as the **natural starting point for early mover brownfield GH2 projects**. While GH2 can replace grey hydrogen as a feedstock in chemical industries such as fertilizer production, its adoption may initially increase OPEX due to the currently higher price of GH2. For industries that can use GH2 as a fuel, such as steel, glass and ceramics, significant CAPEX will be required to retrofit production sites.

The government plays a crucial role in promoting the adoption of GH2 in enterprises through policy incentives, support and the creation of a future marketplace. Figure 4.1 illustrates the potential for brownfield development of green industries in line with a phased and dual strategy and depicts the share of manufacturing industries whose carbon emissions can be abated through the use of GH2 in countries' total export basket. While no data are available for much of Africa (marked in grey), Mozambique, Egypt, Morocco and South Africa appear to have significant opportunities to decarbonize their existing export-oriented industries with GH2, as indicated by their share of "abatable" industries in total exports (WITS, 2023). Morocco and South Africa are considered among the most promising GH2 producer countries. Morocco's OCP Group, for example, recently pledged an investment of USD 13 billion for the period 2023–2027 to green its fertilizer production and mining activities. The country has set ambitious goals for the production of green ammonia by 2027 (1 million tonnes), facilitated by in-house green energy (5 GW) and seawater desalination (560 million m^3) (OCP Group, 2022).

The GH2 production potential of developing countries may be high, but without local up-takers, **greenfield GH2 project development will be necessary to attract new downstream industries**. The competitive marginal cost of GH2 in the mid-term, enabled by abundant renewable energy and short transport distances, may encourage established industrial enterprises to relocate or open new sites in economies with lower operating costs related to (direct or indirect) carbon pricing or the competitiveness of clean energy. This process is referred to as the "renewables pull effect" (for details, see Box 2.2) of countries that draw FDI and the establishment of production sites due to their attractive marginal cost of GH2 (Samadi et al., 2023). This "renewables pull effect" can catalyse the green diversification potential of hydrogen in industry, as exemplified by the relocation of the green iron and steel production industry to Oman, Mauritania and South Africa (Swansy, 2023). Harnessing the renewables pull requires a comprehensive analysis of the investment determinant in the country's energy-intensive industries. While low renewable energy costs attract foreign enterprises, governments should avoid lowering these costs too much, as the potential benefits may quickly evaporate.

The building of a new industrial facility involves significant CAPEX and requires vast amounts of available land. It also provides an opportunity for purposeful construction within a coherent planning framework, e.g. a GH2 industrial cluster (see Section 4.4). By adopting advanced and sustainable GH2 technology from the outset, developing countries can engage in "greenfield leapfrogging", i.e. bypass fossil fuel-based production methods. This strategy mitigates the costs, stranded assets and pollution associated with traditional industrialization.

Figure 4.1. Share of abatable industries in total exports 2022



Source: WITS UN Comtrade - Created with Datawrapper

Early-mover projects in emerging technologies such as GH2 are often perceived as high-risk investments for both brownfield and greenfield developments, particularly in developing countries. While a strong regulatory framework and security are an important precondition, they may not be sufficient to attract investments in GH2 projects. To bridge the initial funding gap and encourage early GH2 adoption in the market creation phase, additional government support for both CAPEX and OPEX is particularly beneficial. Credit-enhancing mechanisms can provide a buffer for private investors, thereby facilitating the entry of senior lending into project structures and attracting institutional investors into the nascent market. De-risking effectively lowers the cost of capital for hydrogen projects, which reduces hydrogen costs and hence drives uptake (Hydrogen Council, 2021).

By fast-tracking access to public funding for GH2 projects, the government can facilitate value chain development and accelerate its suitability for private financing as the market matures. Government can provide direct project funding, co-financing or conditional grants, as well as various government-backed loans (soft, concessional, convertible, contingent, subordinated) to reduce financial risks and provide the necessary upfront capital investment for local industrial projects. According to the Organisation for Economic Co-operation and Development (OECD) (Cammeraat et al., 2022), de-risking public financial instruments can contribute to crowding in private funds, thus maximizing the efficiency of public spending. Government support can have a multiplier effect by tipping the balance in favour of private investment, creating spillovers between investment areas (Mazzucato, 2021). Such financial instruments can cover various phases of project development, including feasibility studies and demonstrations. Public funding should be offered at the inception of the GH2 value chain to support first movers and to keep the impact on government budgets low (IRENA, 2022a). For example, in its NHS, Chile announced that it will launch a funding round of up to USD 50 million to support companies and (inter-)national consortia in investing in scalable and replicable GH2 projects in the country. Even though such mechanisms may be challenging for many developing countries to finance, sensible public investment is a key enabler for long-term public benefit.

Blended finance, which combines concessional public funds with commercial funds, can be a powerful means to direct more private finance towards impactful investments that are unable to proceed on strictly commercial terms. One of the most compelling aspects of blended finance is that it uses relatively low amounts of strategic public or institutional funding (e.g. from the Global Environment Facility) to rebalance a project's risk profile. By infusing concessional funding (such as grants or low-interest loans), pioneering investments become attractive to private investors, particularly in emerging markets where high investment risk perceptions prevail (Mutambatsere et al., 2022). Initiatives such as the SA-H2 Fund and SDG Namibia One have raised over USD 1 billion to accelerate the development of South Africa and Namibia's GH2 industry through innovative blended finance solutions (Engineering News, 2023).

The blended finance approach unlocks new sources of financing for development projects considered too risky or unattractive to private investors alone. Thereby, **crucial support for innovators can be provided during their growth stage, helping to finance higher-risk demonstration projects** (EIB, 2022). Introducing additional provisions such as implementing risk-sharing mechanisms to mitigate offtake-, technology scale-up- and operational risks, as well as ensuring flexibility in terms of loan tenor to help match the long economic lifespan of hydrogen assets is also recommended. Public support for R&D may also be necessary for complex demonstrations of applications at low-technology readiness levels. This applies to the steel industry, for example, which requires further refinement and demonstration of DRI produced with 100 per cent hydrogen. It also applies to further explorations of the emerging option of ammonia. De-risking efforts can facilitate large-scale demand for hydrogen and hydrogen-based products, including improvements and innovations related to hydrogen storage (IEA, 2019).

Public funding support schemes can be used for competitive bidding processes to create a market for project development. Through calls for project proposals and a competitive bidding process, the government can select the most promising projects. This approach encourages project developers to submit high-quality proposals while ensuring that the government supports the most viable projects. Competitive bidding promotes transparency and fair competition in the allocation of resources or contracts. It can be used to award subsidies, grants, incentives or other forms of financial support to projects that meet specific criteria or objectives. Blended finance mechanisms can also be awarded through a competitive bidding process (IRENA, 2023a). In Oman, for example Hydrom, a large independent GH2 entity, awards government-owned parcels of land to GH2 projects through bids on an online auction platform. Winning developers are expected to deliver integrated projects covering the full GH2 value chain, and to partner with a government-owned entity.

Government can also play a crucial role in **supporting early-stage (high-risk) GH2 projects by providing equity financing** in exchange for a stake in the project. This injection of venture capital not only helps mitigate the financial risks associated with such projects but also boosts investor confidence, as the government's investment demonstrates its commitment to the project's success. By taking equity shares in such early movers, governments move beyond de-risking and lead by example, taking risks as well and potentially earning returns on their public investment. Furthermore, public ownership offers advantages in terms of ensuring benefit-sharing and allows the government to have a say in project operations beyond its regulatory role. It is important to establish conditions such as reinvestment of profits and restrictions on share buy-backs to ensure that public investment is structured less like a handout and more like a market-shaping strategy, driven by public objectives (Mazzucato, 2021). For example, Namibia's government acquired a 24 per cent equity stake in Hyphen Hydrogen Energy, and expects the value of these shares to increase substantially by the end of the feasibility study. This provides flexibility for the government to decide whether to retain, sell or dilute its interest based on the project's success and the equity investment's potential, securing a favourable return on its investment. Moreover, the project is expected to employ an estimated 3,000 workers, with 15,000 construction jobs supported over the four-year construction period. Over 90 per cent of these jobs are expected to be filled by local Namibians (The Brief, 2023).

The global bonds market with a debt volume of around USD 100 trillion is twice the size of the equity market (valued at USD 50 trillion). This vast pool of resources can be effectively mobilized to support GH2-based industrialization. **Green bonds, which are fixed-income securities specifically designed to finance environmentally sustainable projects, such as green goods manufacturing** (Mathews, 2023), have gained significant traction in recent years. It is projected that green bond issuances will grow from USD 0.5 trillion in 2021 to USD 5 trillion by 2025, and are likely to play a role in absorbing investment in GH2 projects (ibid). Green bonds are typically issued by governments (sovereign), private entities (corporate), or national and multi-national development banks. Major issuers offer a favourable risk ratio, reducing the financing risks associated with these projects while being accountable to investors regarding the management of proceeds and the environmental impacts. This fosters confidence and encourages long-term involvement (Pavlovic, 2021). Consequently, bonds serve as a powerful tool in redirecting substantial capital investments from fossil fuels to sustainable green projects such as GH2 initiatives. To harness the full potential of the bond market for the hydrogen industry, development finance and commercial banks should incorporate GH2 into their green financing and investing taxonomies. The introduction of "hydrogen bonds", tailored to the unique characteristics of GH2 investments, would facilitate the use of the bond market for the hydrogen industry.

Fiscal incentives can provide crucial financial margin for a GH2 project to succeed. These can take the form of tax credits, exemptions, rebates or deductions, which are straightforward and effective supply-side mechanisms that do not require upfront budget expenditure. These incentives can be granted for either investments (per $, supports CAPEX) or production (per output, supports OPEX). Investment tax credits or accelerated depreciation reduce the tax burden of GH2 investments through earlier write-off, thereby attracting private capital (IRENA, 2022a). Such tax reductions can boost project development activity but could also lead to government missing out on potential tax revenue – this trade-off must be carefully weighed in advance. Subsidies, on the other hand, which might be constrained by budget limitations, could potentially be provided by multilateral development banks or donor countries. They are an effective means to make the use of GH2 in production more economically viable. For example, offering a price premium on GH2 for steel producers (see Section 4.3) that are starting to use GH2 as an input can compensate for higher OPEX. Such an approach could be designed to temporarily and gradually phase out the premium price as the cost of green steel production becomes more competitive. Subsidized OPEX of GH2 adopters translates into lower market prices and thus increased competitiveness of green goods, driving sustained demand.

First-loss guarantees can play a crucial role in providing direct financing for developing countries. This mechanism involves a public funding source (e.g. government, development banks, national programmes or export credit agencies) offering a guarantee to eligible projects. Senior project lenders can thereby reduce their risk exposure within predefined parameters (EIB, 2022). If the project succeeds, the public guarantee would not be used, thus avoiding any draw on public resources. The guarantee can be linked to the local value chain addition by the GH2 investment to ensure that it generates local benefits beyond simply the GH2 project. This instrument can serve as an incentive for the initial development of GH2 value chain projects, with the potential of gradually phasing out public support as the need for it diminishes. It is important to note that sovereign guarantees, i.e. guarantees backed by the government directly or through a state agency, bear substantial financial risk. Industrial projects initially incur losses and GH2 is not expected to be price-competitive before 2030 in the face of grey alternatives (depending on factors such as carbon pricing). Given this inherent uncertainty, the question arises who will be willing to bear the financial risk necessary to jumpstart the GH2 industry. Even if most guarantees remain unused, the failure of a single project can have a major impact on the budget. Consequently, first-loss guarantees should only be offered following a comprehensive risk assessment on a case-to-case basis, including a thorough evaluation of the project's business plan. Alternatively, a development bank or other donor could provide such guarantees.

Box 4.2. Just Energy Transition Partnerships (JETPs)

Just Energy Transition Partnerships (JETPs) are a new financing mechanism that assist heavily coal-dependent emerging economies in their just energy transition efforts through concessional loans. These partnerships support countries as they shift away from coal production and consumption, addressing social consequences through worker training, job creation and economic opportunities for affected communities. The first JETP, established at COP 26 in Glasgow, pledged USD 8.5 billion for South Africa, with additional partner countries, namely India, Indonesia, Viet Nam and Senegal announced later. The donor pool has increased to include multilateral development banks and development finance agencies, enabling faster progress compared to UN climate talks, where oil and gas-producing countries may block agreements. South Africa's JETP Implementation Plan, released at COP 27 in Sharm el-Sheikh in November 2022, outlines priority investments in the electricity and GH2 industries, totalling investment needs of USD 98 billion. This highlights the significant scale of change necessary for a just energy transition (IISD, 2022).

4.3. Demand creation policies

The GH2 market's growth has brought the issue of demand to the forefront: **can downstream industries afford to absorb locally produced GH2, and will the GH2 industry's products find enough buyers?** Policymakers have several options to stimulate commercial demand for GH2 in multiple applications across end-use industries and for the green goods they produce. Demand-side policies can strategically kick-start markets and provide downstream users with visibility on the GH2 value chain's trajectory. This can help reduce the cost competitiveness gap, increase investor confidence and attract investments from equipment manufacturing to infrastructure. Over time, economies of scale will take hold, enabling the different applications to mature into self-sustaining market competitiveness (EIB, 2022).

Certifications will play a pivotal role in assuring the green value of goods produced with GH2. Certifications are a standardized and reliable means to verify and validate products' emissions performance and their sustainability credentials, for example certifying that the hydrogen used in the manufacturing process was produced from renewable (or low-carbon) sources. They help establish trust and transparency in the market by ensuring that producers' claims their goods' green attributes are credible and backed by independent assessment. This is crucial to pull forward demand with the willingness to pay a green premium (the price difference between green and regular goods), and to thus establish green goods as an export commodity. Moreover, certifications create market incentives for producers to adopt GH2 and other clean technologies, as certified products often enjoy preferential treatment in procurement processes or in consumer preferences. Product labelling can further extend the visibility of green goods' unique selling proposition to consumers. Section 6.5 provides additional insights on the international coordination aspect of certification in the context of green product trade.

Green public procurement is an established policy instrument to help scale up value chains through public sector investment (Baker, 2021). Governments can play a crucial role in creating a stable initial driver of demand for (certified) green goods produced with GH2. For example, governments can promote the creation of a market for green steel by prioritizing its use in government-funded construction projects, including buildings, bridges, railways and transport fleets (IRENA, 2022a). By choosing to spend slightly more to cover the green premium of GH2 producers rather than resorting to traditional providers, governments can stimulate demand, support producers and set an example for others to follow suit. This approach can be considered as an alternative to direct subsidies for green goods produced with GH2, with government funding serving as a market shaper rather than a hand-out. Additionally, public procurement can consider the local content of goods, favouring those with a higher share of domestically manufactured components and local employment.

Box 4.3. Green goods certification insights

As the GH2 industry is still in its nascent years, the development of specific certification schemes is still ongoing. Certifications play a crucial role in verifying the sustainability of the entire supply chain, e.g. from hydrogen production to the final product, or specific parts of the supply chain, typically up to the point of production. These schemes assess a number of factors such as the hydrogen production process' carbon intensity, the use of renewable energy sources, the reduction of lifecycle emissions, and adherence to environmental standards. They involve rigorous assessment processes, including third-party verification and compliance with established criteria and standards. Monitoring monthly additionality ensures continued compliance by measuring the incremental impact of the certified activities in reducing carbon emissions beyond the predefined baseline of the business-as-usual scenario. While a certification of green attributes is essential for the export of green goods, obtaining certification from export destinations can be quite costly. Robust data collection and monitoring systems include regular data submissions, verification by independent auditors, and adherence to standardized protocols or methodologies established by the certification scheme. Voluntary certification schemes, such as the Steel Climate Standard (Global Steel Climate Council and Trinity Consultants, 2023), promote compliance among producers. It is important to avoid weak or diluted certification conditions and institutions to maintain trust in the green goods market.

Governments can **stimulate demand for green goods produced with GH2 by offering financial incentives to prospective end users** in the market. These incentives can take the form of subsidies, price premiums and tax rebates, targeting the downstream segment of the GH2 value chain. By offering subsidies or tax rebates at the production, purchase or end-user levels, governments can effectively lower OPEX for green goods manufacturers, resulting in lower prices and increased demand for such goods. Price support measures such as revenue top-up and stabilization mechanisms can also be implemented. To finance these incentives, developing country governments may opt for tax rebates, while subsidies and price premiums could potentially be funded by multilateral development banks or donor countries. Linking these incentives to industrial performance criteria can further maximize their impact. Section 6.4 explores the options of policy support financing from the Global North to the Global South.

Quotas and targets can provide additional support to generate demand and foster a stable market. They can address various entry points into the GH2 value chain:

1. Quotas for minimum quantity of GH2 used in specific market segments;

2. Legal or voluntary targets to meet CO_2 intensity goals at a sectoral level (similar to low-carbon fuel standards) or to provide a given share of output from low-carbon inputs (as with renewable transport fuel obligations).

Such quotas and targets are particularly effective when coupled with price support mechanisms and purchase incentives. Governments must, however, consider the challenges and costs of their implementation.

Correcting market distortions that disincentivize new renewable technology adoption is crucial to ensure GH2's competitiveness. One effective approach is **phasing out fossil fuel subsidies** in exchange for upstream exploration and downstream price subsidies for customers (Hydrogen Council, 2021). Even though this requires compensation instruments to ensure social acceptance, it is an effective means for governments to tilt the industrial energy market in the desired direction. This does not require public spending: the amount saved from eliminating fossil fuel subsidies can be used for GH2 support measures, thereby achieving a double impact. Reducing support schemes for established energy sources for heat and fuel may be politically challenging due to the resulting changes in costs for consumers and industry alike. Redirecting some of the savings to other less harmful sources can facilitate the transition for individual consumers and industry. For example, compensating lower- and middle-class households with cash payments tied to their loss of benefits can help mitigate affordability concerns. This is already the case in Saudi Arabia, for example.

Following successful project inception, downstream industrial GH2 applications such as in steel, chemicals and refineries may necessitate specific support to ensure that offtake sufficiently covers operating costs. This support can assume the form of **offtake or price guarantee schemes**, which often replace previous forms of direct assistance:

1. **Offtake guarantees** are contractual agreements whereby a buyer commits to purchasing a predetermined quantity of GH2 at a specified price over a predefined period. This arrangement secures a stable income stream for the project developer, regardless of price fluctuations in the hydrogen market.

2. **Price guarantees** entail commitments by a government or other entity to pay a predetermined price for GH2, irrespective of the prevailing market price. The project developer is thereby guaranteed a fixed price for the GH2 produced, mitigating the risk of price fluctuations in the market. However, this does not guarantee that the project will sell all of its GH2, as the developer must still compete against other producers in the market.

Ensuring transparency and planning security are essential when allocating budgets for GH2. A clear outlook on the expected support regime for a minimum of 5-10 years in advance must be provided when project delivery relies on public support. This can be achieved by establishing a schedule of public support budgets, committing to a minimum volume of projects, and defining transparent decision rules for adjusting subsidization based on technological advancements. Given the time-intensive nature of hydrogen projects, this level of visibility significantly reduces risk and enhances the attractiveness of projects for financing (Hydrogen Council, 2021).

4.4. Value chain integration and coordination

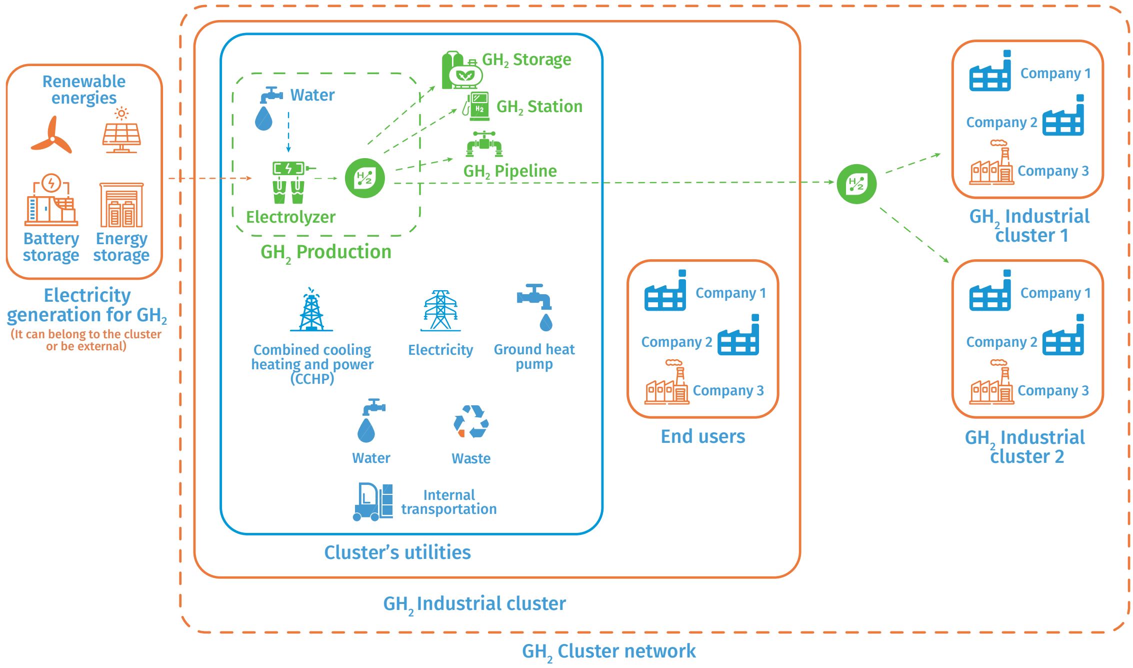
To successfully embark on GH2-based industrialization, developing countries should prioritize the formulation of robust industrial policies, conduct investment evaluations and engage in strategic foresight. Their hydrogen industry plans and policies must be well-designed and coordinated, with a focus on stimulating economic linkages. They must contribute to local industrial development and foster the growth of a local supply industry for GH2 components and equipment to avoid common pitfalls and prevent new patterns of dependency. This approach will enable developing countries to maximize the benefits of GH2-based industrialization and promote sustainable development (Fokeer et al., 2022).

Government can play a pivotal role in mitigating the salient risks associated with a new chapter of industrial development, such as the complexity of the value chain. **Many potential coordination challenges in the emerging GH2 market can be effectively navigated with a comprehensive and integrated industrial policy approach that encompasses the entire value chain.** This requires aligning and optimizing projects across the value chain to simultaneously nurture various dimensions of the GH2 ecosystem. Coordination efforts may include the identification of relevant projects, the screening of promising use cases and the prioritization of public investments (EIB, 2022). Governments can also address coordination challenges by orchestrating the timing of private sector investments, possibly through the provision of guarantees. Achieving effective value chain coordination requires a robust implementation strategy in addition to a sound policy logic (Mazzucato and Kattel, 2023): most contemporary industrial policies are implemented in a “waterfall moment” following lengthy decision-making processes that separate policy design from institutional learning and implementation. Continuous and gradual experimentation or trials to determine the most effective policies can yield multiple solutions and foster ongoing learning.

Until GH2 finance mechanisms and business plans have sufficiently matured, projects with sizable investments, such as commercial-scale greenfield industrial site development, could benefit from a **public-private partnership structure** (or even public ownership). This approach involves a combination of direct public investment and multi-stage competitions to award contracts, often through a public enterprise, as is the case in Oman, for example. By adopting such partnerships, **sector collaboration can be encouraged around key projects while avoiding the selection of winners from the outset.** In addition to open collaboration initiatives, the establishment of working groups and export panels can nurture a deeper understanding of the evolving market, economic, regulatory and environmental contexts (EIB, 2022). This facilitates the exchange of knowledge and learning among stakeholders, ensuring a more informed decision-making process. To mitigate risk, a gradual approach can be adopted, starting with the funding of smaller projects to reassure investors (IEA, 2019). Subsequent projects can benefit significantly from the lessons learned and knowledge gained from initial projects, while also increasing awareness of available public funding and partnership options.

Green Hydrogen Industrial Clusters (GHIC) are industrial regions or clusters that share GH2 (production, transport and use), renewable energy electricity and other resources for various purposes, including material production, heating and cooling, local mobility and industrial feedstock (UNIDO, 2023a). The development of GH2 industrial clusters can be facilitated through public initiatives devised by local authorities, partnerships with the private sector and optimized government spending. These clusters serve as hubs to grow GH2 demand, particularly in industries such as refining, ammonia, methanol and steelmaking (IEA, 2019). To effectively develop interdependent GH2 projects, **a value chain approach that focuses on suitable geographical locations is key.** By identifying potential cluster development sites where multiple end-users can share GH2 production, transport, storage capacity and green goods manufacturing, any associated costs and risks can be shared, resulting in a reduced levelized cost of hydrogen (UNIDO, 2023a). For example, collaborative procurement among all end-users in a cluster may involve the conclusion of long-term contracts for future GH2 supply, thus pooling buying risk based on the anticipated demand scale and timing while offering more certainty for investors (IEA, 2019).

Figure 4.2. GH2 cluster model



Source: UNIDO, 2023a

The sharing and efficient use of resources within a cluster can significantly reduce energy and material waste, thereby enhancing sustainability. For example, excess heat generated by one industry can be effectively utilized by adjacent industries, thus conserving energy. Additionally, implementing circular economy initiatives within clusters can play a crucial role in waste management and recycling. By promoting the recycling and reuse of key materials, clusters can minimize waste and decrease reliance on raw materials. That is, incorporating circular economy principles into cluster design can enhance the industry's economic and environmental performance. The integration of industrial GH2 end-use applications in coastal hubs holds immense future potential. By establishing such hubs, access to port facilities can be ensured, allowing for efficient GH2 trade through international shipping routes. Moreover, these hubs can also serve as a platform for using GH2 and its derivatives as fuel for shipping and trucking. The proximity to offshore wind and solar PV energy sources in certain locations further enhances the viability of coastal hubs for GH2 integration (Clean Hydrogen Joint Undertaking, 2023).

Authorities play a crucial role in facilitating the development of consortia among companies along the GH2 value chain. These consortia can work together to devise solutions that reduce the high initial investment required for cluster development. The need for extensive upfront investment in transmission and distribution infrastructure can be minimized by co-locating GH2 demand and supply, for example (IEA, 2019). Additionally, existing industrial hubs with established hydrogen users for refining and chemicals, including ammonia, can leverage their infrastructure, thus reducing the need to develop demand for equipment in new sectors. For instance, the H2AR Consortium in Argentina serves as a collaborative workspace for companies engaged in the hydrogen value chain, from production to application, fostering innovation and accelerating local market development. Various actors, including hydrogen producers, consumers, utilities and infrastructure companies collaborate on pilot projects to define efficiencies, costs and operation parameters, providing investment signals for the industry's growth in the local market. This collaborative approach aims to expedite innovation and the advancement of Argentina's hydrogen industry.

Box 4.4. Chile: Antofagasta GH2 hub

Chile, as the first Latin American country with an NHS, is committed to fostering a thriving GH2 industry. The Antofagasta region plays a key role in this endeavour due to its abundant solar and wind resources, coastal location and strategic position in the GH2 value chain. With a potential solar capacity of 1,400 GW, the region presents ideal conditions for GH2 initiatives. There is significant hydrogen demand in the mining, explosives and fertilizer industries, with Antofagasta PLC planning to adopt hydrogen-based transport and green ammonia for blasting operations (Antofagasta PLC, 2022).

Chile's NHS outlines ambitious development plans until 2050, aiming for 38 GW of electrolyser capacity and an annual GH2 production of 2.8 million tonnes and 5.6 million tonnes of green ammonia in Antofagasta by 2050. The GH2 industry's economic impact is substantial, with projections of generating around USD 700 million in annual tax revenues, benefitting at least one quarter of existing companies, and creating thousands of jobs by 2050. Careful planning can optimize water supply synergies through new desalination capacities. However, to achieve these goals, over USD 70 billion in cumulative investments are needed by 2050, with renewable capacities comprising between 40 per cent and 65 per cent of total investments, followed by hydrogen generation (13 per cent to 32 per cent), hydrogen conditioning and derivatives synthesis (9 per cent to 17 per cent), electrical infrastructure (3 per cent to 13 per cent), and export ships (2 per cent to 11 per cent) (Altmann et al., 2022). CORFO, Chile's Economic Development Agency, has selected project proposals to accelerate GH2 production plant development in Antofagasta, with operations commencing by December 2025. "Antofagasta Minería Energía Renovable (AMER)", led by Air Liquide SA, plans to produce 60,000 tonnes of e-methanol annually, contributing substantially to the region's GH2 efforts with an 80 MW electrolyser, supported by USD 11.7 million in CORFO funding. Additionally, ENGIE SA's "HyEx" project aims to generate 3,200 tonnes of GH2 annually, reducing over 30,000 tonnes of CO_2 emissions yearly by supplying Enaex for green ammonia production, with USD 9.5 million in CORFO funding.

The implementation of comprehensive training and educational initiatives prioritizing the value and safety of GH2 is crucial to effectively address knowledge gaps and skill shortages. By conducting broad educational campaigns centred around GH2 technologies, public awareness of hydrogen and its important role in achieving low-carbon development objectives can be successfully raised. Additionally, targeted training programmes can effectively enhance the workforce's skill set, equipping workers with practical capacities that align with the emerging GH2 value chain. Such programmes also have the potential to address concerns surrounding a Just Transition. For instance, the Government of India announced a coordinated skilling programme in its 2023 *National Green Hydrogen Mission* document, which will bring together institutions, training centres, universities, industry and businesses to incorporate global best practices and developments.

An in-depth understanding of safety measures for hydrogen and its derivatives, particularly ammonia, is crucial to guarantee the secure implementation, operation and maintenance of hydrogen and fuel cell equipment. Hydrogen safety training encompasses two major categories: (i) awareness training, and (ii) professional training. Awareness training is designed to cater to a diverse range of stakeholders, including the general public, early adopters of hydrogen and fuel cell (HFC) technologies, and professionals from various fields associated with hydrogen technologies. This type of training typically covers fundamental aspects of hydrogen properties and emergency response protocols. On the other hand, specialized professional training can be tailored to specific groups, including:

- hydrogen technicians
- gas and pipe fitters
- design engineers
- installers
- operators of hydrogen production and utilization equipment
- authorities having jurisdiction (AHJs)
- first responders

By offering targeted education and training programmes, governments can ensure that professionals in different industries obtain the necessary skills and knowledge to safely engage with hydrogen technologies.

To enhance the hydrogen industry's growth and competitiveness, governments should actively encourage knowledge exchange between businesses, and ensure that new market entrants gain access to previous R&D efforts and demonstration projects that have received public funding. This is particularly important given the concentration of knowledge in the hydrogen value chain in terms of patents and trademarks – future growth of project scales and financial requirements could further intensify this concentration, leading to higher prices for GH2 in the long run (Cammeraat et al., 2022). By supporting demonstration projects, companies gain practical experience and valuable knowledge through learning-by-doing. Public support for such projects should be contingent on (at least partial) knowledge sharing. In the emerging international GH2 market, certain enterprises may be reluctant to share valuable information to protect their competitive advantage. The government's role is thus to incentivize knowledge sharing while maintaining a strong investment case for businesses. Funds could be directed towards consortia instead of individual businesses, thus facilitating the diffusion of innovation and cost reductions throughout the value chain. In addition, intra-governmental coordination and information exchange can help optimize the use of knowledge and resources by avoiding duplication of demonstration costs.

Creating centralized digital public matchmaking platforms that connect funding options with stakeholders can be a major catalyst for project financing. Currently, the lack of a well-established GH2 financing ecosystem means that many projects primarily/initially rely on public funding, often with limited knowledge of available options. Similarly, prospective GH2 investors may face challenges in navigating multiple financing streams, each with its own bureaucratic hurdles. Matchmaking platforms managed by the government can streamline the selection and allocation process for both investors and developers, effectively reducing coordination barriers (IRENA, 2022a). By combining the reliability and inclusiveness of a centralized platform with a user-friendly digital interface ensures accessibility and ease of use.

Box 4.5. Knowledge sharing in Chile's solar energy industry

The Chilean Economic Development Agency (CORFO) has made significant strides in the development of Chile's solar energy industry since 2016. Despite its focus on the national solar industry, multiple industries and stakeholders are effectively involved. Two key instruments were established to strengthen coordination among various actors and sectors (Mazzucato and Kattel, 2023):

- An inclusive and collaborative platform which facilitates co-creation and knowledge exchange. By embracing a bottom-up approach, it enables the active participation of both public and private sector actors, fostering mutual trust and synergies. Through this collaborative endeavour, a shared vision can be developed, thus ensuring collective ownership and engagement.

- A dedicated clean technology institute which serves as a hub for interdisciplinary research focused on advancing solar energy solutions. By encouraging cross-disciplinary collaboration, the institute brings together experts from various fields to explore innovative approaches and address technical and economic challenges. This targeted public sector support is crucial in driving progress in the solar energy industry.

Government-backed advisory services can provide targeted support and guidance to project promoters and help them navigate the evolving financial landscape (EIB, 2022). Expertise in navigating risks and in blending finance solutions specifically for GH2 projects is essential. To effectively address the complexities and lengthy development timelines of GH2 projects, advisory resources should be adequately sized and tailored. In addition to providing guidance, advisory services can offer hands-on project development assistance for large-scale ventures involving multiple stakeholders and value chain segments. Having a neutral advisory partner can accelerate decision-making and project activities. Advisory services also play a fundamental role in mitigating uncertainties by facilitating the review of financing, economic and technical alternatives that influence project viability and bankability. For instance, such support can be used to explore avenues to aggregate demand around GH2 production centres or integrate PtX in renewable energy projects. To deliver on this, advisors must have in-depth industry knowledge, including in GH2 production and equipment. By leveraging advisory support, projects can access potential financing faster and position themselves for necessary public support or guarantees to ensure bankability.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5. Transport and distribution policies

Transport and distribution networks, along with the necessary infrastructure, play a crucial role in efficiently moving GH2 from production sites to consumption destinations. Hydrogen is mostly produced on-site in clusters that co-locate production and demand. In the future, however, as economies of scale improve, it may become more profitable to establish large-scale hydrogen production facilities and distribute hydrogen to users that are located farther away (Cammeraat et al., 2022). Section 6.5 examines potential trade routes and patterns in more detail.

As global demand for GH2 continues to rise, both production volumes and transport distances will increase. This will necessitate the development of a centralized GH2 production system that includes a comprehensive hydrogen storage and transport infrastructure. This network will connect regions with favourable GH2 production conditions to demand centres in domestic and international markets. International coordination will be essential in cross-border GH2 trade to ensure the infrastructure's effective functioning. Retrofitting and repurposing the existing natural gas networks, as well as constructing new dedicated hydrogen infrastructure will be required, including:

- pipelines
- ports and terminals
- cargo ships and trains for hydrogen and its derivatives
- large-scale hydrogen storage
- conversion technologies and plants
- refuelling station networks for hydrogen-powered trucks, ships, planes and trains
- upgraded transmission networks to harness renewable energy potential

The low energy density of hydrogen compared to natural gas presents significant technical challenges when repurposing existing infrastructure. One cubic meter of hydrogen contains only one-third of the energy found in one cubic meter of natural gas at equivalent pressure and temperature. Moreover, hydrogen has a considerably lower boiling point of -253 °C compared to -162 °C for natural gas. The transmission of hydrogen therefore necessitates a conversion of hydrogen into a form with higher density, such as liquefaction or transformation into substances such as ammonia, LOHC or synthetic hydrocarbon fuels (IRENA, 2022c). Not only do these hydrogen derivatives have higher energy density, they are also more suitable for long-distance trade and transport.

The large-scale conversion and reconversion of hydrogen present significant challenges, including high energy consumption and technological uncertainties. This ambiguity contributes to the overall costs of hydrogen production (Roland Berger, 2021), and directly impacts the profitability and perceived risks of GH2 projects. As a result, investments in GH2 have primarily focused on production and end-user applications. To achieve widespread GH2 adoption and decarbonization, efficient transportation solutions for GH2 must be developed. This requires planning relevant hydrogen infrastructure projects early on in alignment with the broader hydrogen strategy. Local infrastructure requirements for hydrogen transport need to be evaluated to identify the appropriate economic model for transport infrastructure and efforts between the public and private sectors need to be coordinated. Policymakers should take these key considerations into account when planning, regulating and financing a GH2 transport network. By addressing these factors, the development of GH2 infrastructure can be effectively integrated with the country's overall hydrogen strategy, enabling efficient GH2 transportation and accelerating its adoption for decarbonization purposes.

5.1. Planning GH2 infrastructure, transport and storage

The government plays a leading role in identifying domestic and international routes and preferred transport solutions and GH2 infrastructure, which should be outlined in roadmaps and strategies. Aligning these strategies with concrete long-term energy plans is crucial to attract investment and maximize planning efficiency. The capital-intensiveness and long-term nature of such infrastructure projects involves detailed planning based on considerations of the projects' potential to create long-term dependencies for industrial and residential users (IRENA, 2021). Cross-border integration can further bolster infrastructure capacity plans and improve the overall system's efficiency by linking production and demand centres (Hydrogen Council, 2021). The successful growth of the global liquefied natural gas (LNG) market is a valuable lesson in international collaboration between the government, industry and other stakeholders that can be leveraged to achieve this goal.

Robust public policies must be implemented to support the development of a GH2 grid. Repurposing parts of existing fossil gas infrastructure to accommodate GH2 transport is a cost-effective approach that capitalizes on existing infrastructure while meeting growing GH2 demand. Prior to initiating the gas grid's conversion to hydrogen, policymakers should conduct comprehensive planning assessments as an initial step to identify "no-regret" areas for hydrogen pipelines based on industrial demand. Furthermore, the transport sector's projected increase in demand should be considered when determining pipeline placement. These planning assessments will not only identify necessary supply lines but can also help mitigate the risks associated with oversizing, stranded assets or abandoned projects. Avoiding failed green hydrogen projects is important, to avoid political frustration and backlash against further decarbonization projects.

The following guiding questions serve as a starting point for developing hydrogen infrastructure plans, offering policymakers in both developed and developing countries valuable insights (BMBF, 2021):

What is the desired balance between privately owned infrastructure and open-access systems?

Privately owned infrastructure presents several advantages, such as providing investment incentives, promoting competition and fostering innovation. However, an overreliance on private ownership may result in uneven distribution, lack of coordination and potential market failures. Open-access systems, on the other hand, have the potential of ensuring fair market access, preventing monopolies and encouraging collaboration, but may encounter challenges in terms of funding and maintenance if not well-regulated. Policymakers can strike a balance that encourages private investment while ensuring fair competition and accessibility. To achieve this, regulatory frameworks should address potential monopolistic tendencies, ensure cost recovery and safeguard against infrastructure gaps.

What are the most viable domestic GH2 storage options, considering both physical (location, geological features) and chemical (carrier) aspects?

Physical storage options such as salt caverns, depleted gas reservoirs and aquifers, provide large-scale and long-duration storage capabilities, but may be limited by geological constraints. On the other hand, chemical carriers such as ammonia can facilitate hydrogen transport and provide energy density benefits, but entail energy conversion losses and the need for additional infrastructure. To design an optimal storage system, policymakers need to evaluate the geological features of available sites and consider integrating both physical and chemical storage options to ensure the storage system's flexibility, reliability and cost-effectiveness.

Should electrolysers be located close to the centres of renewable energy supply, with storage options placed centrally in the grid? Or should both rather be located in the vicinity of demand?

Co-locating electrolysers with renewable energy sources offers numerous benefits, including reducing transmission losses and enhancing overall efficiency in GH2 production. However, focusing exclusively on proximity to renewable energy sources may inadvertently lead to transport constraints for the produced GH2 and to the underutilization of other potential sites. To enhance supply reliability, policymakers should consider locating storage facilities closer to demand centres. Policymakers should take local factors such as existing infrastructure, renewable energy availability and demand patterns into account. Strategic priorities, including the share of GH2 for export, should also be considered to optimize the location of electrolysers and storage facilities. A balanced approach helps avoid future lock-in effects.

Is regional/international coordination or an integrated decision process necessary for infrastructure planning/development to efficiently integrate GH2 into the energy system in terms of technology and costs?

Regional/international coordination has the potential to unlock significant benefits, such as economies of scale, optimized resource utilization and knowledge exchange. By implementing an integrated decision-making process, policymakers can streamline planning, reduce redundancy and ensure compatibility across regions. However, coordination efforts may encounter political and logistical challenges, and an integrated process may require extensive data sharing and stakeholder engagement. Despite these challenges, policymakers should prioritize cooperation among regions and nations to establish common technical standards. When concerns related to sovereignty, security and data sharing are addressed, all parties involved can reap the benefit of regional/international cooperation.

Should hydrogen and electricity infrastructure be planned within an integrated framework or separately?

An integrated framework enables cross-sectoral planning, fostering synergies between hydrogen and electricity systems. This approach ensures flexibility and addresses specific sectoral needs. Integrated planning entails complex coordination and decision-making processes. On the other hand, separate planning may overlook opportunities for efficiency gains and system optimization. Policymakers must carefully evaluate the advantages of integration while considering the interdependence between hydrogen and electricity infrastructure. By aligning policies accordingly, they can find a balance between reaping the benefits of integration and mitigating the challenges involved.

How can decision-making processes for hydrogen network planning accommodate uncertainties related to demand, production sites and import routes, while also considering the critical long-term role of decarbonization?

Uncertainties may lead to potential delays in infrastructure development. Balancing immediate needs with long-term goals is key for effective and sustainable planning. Adopting flexible planning methodologies such as a scenario-based approach to address uncertainties may prove beneficial. These methodologies allow for the incorporation of various potential outcomes, enabling adaptive infrastructure development. By setting long-term decarbonization goals, policymakers can take strategic decisions and avoid lock-ins to high-carbon pathways. To ensure resilience and alignment with decarbonization objectives, policymakers should conduct robust scenario analyses, engage with stakeholders and continuously review and update their plans in response to evolving technologies and market conditions. This approach enables them to navigate uncertainties and achieve sustainable infrastructure development.

How can public engagement be effectively cultivated to gain support for new large-scale GH2 infrastructure projects?

Public engagement builds trust, raises awareness and contributes to project legitimacy. By involving stakeholders, policymakers can foster a sense of ownership and gain valuable insights into potential concerns and benefits. To ensure effective engagement, policymakers should design inclusive and transparent processes that prioritize accurate information dissemination, address public concerns, and emphasize the societal and environmental advantages of large-scale GH2 infrastructure projects. By actively involving the public, policymakers can create a foundation of support and promote the projects' successful implementation.

5.1.1. Pipelines vs maritime transport

The repurposing of existing gas pipelines for the transportation of hydrogen is a feasible and cost-effective option. Onshore or offshore **pipelines are the preferred choice for hydrogen transport.** They are the most efficient and inexpensive means for transporting hydrogen, with a range of up to 2,500 km to 3,000 km (IEA, 2022c). The global natural gas transmission pipeline network is extensive, currently spanning over 1.2 million km, with an additional 200,000 km of pipeline projects in various stages of development. However, as the pursuit of net-zero emissions goals continues, there may be a decline in natural gas consumption over time, which could result in stranded assets within the gas network. Some researchers advocate the repurposing of part of the existing infrastructure to enable hydrogen transport, though the long-term technical and economic feasibility are still a subject of debate.

The transition to 100 per cent hydrogen supply poses a huge challenge. Achieving full conversion requires an immediate shift to 100 per cent hydrogen within each segment of the affected network. This entails the installation of new compressors, storage facilities and the replacement of meters, compressors, monitoring equipment and existing gas appliances. To ensure cost-effectiveness, the dimensioning of repurposed pipelines must be optimized while meeting capacity requirements. Offshore pipelines are associated with unique challenges, including pressure limitations, fatigue cracking and embrittlement, necessitating further research to ensure their suitability for hydrogen transport. However, if and once these technical barriers are overcome, the repurposing of gas pipelines for hydrogen provides a faster and more cost-effective alternative to building entirely new dedicated hydrogen networks (for more details see Section 5.3), while also mitigating the risks associated with stranded assets. It should be noted, however, that the long-term technical and economic viability of repurposed pipelines remains a subject of debate due to the absence of precedent cases. The feasibility of repurposing gas pipelines for hydrogen transport hinges on two conditions (IEA, 2022c):

1. the presence of unused or under-used pipelines alongside existing ones that can continue to meet demand for natural gas; and

2. the existence of a sizable hydrogen market with significant initial uptake, which will attract more users once the network is established.

Both natural gas transmission and dedicated hydrogen pipelines typically use carbon steel materials. However, it is worth noting that hydrogen-specific standards, such as the "ASME B31.12" code for inland hydrogen pipelines, impose stricter requirements compared to their natural gas counterparts (ASME, 2020). This is due to hydrogen's ability to reduce the ductility and fracture toughness of pipeline materials, as well as to increase the rate of fatigue growth. Hydrogen's chemical properties can lead to hydrogen embrittlement, a phenomenon where the presence of hydrogen induces cracks in the steel, thereby accelerating pipe degradation. Nevertheless, there are viable options to address these potential challenges, which can vary depending on the specific pipeline (IEA, 2022c):

- Regularly monitor pipeline integrity using methods such as in-line inspections and pigging;

- Apply a hydrogen barrier coating to provide protective measures for the pipelines;

- Optimize pipeline pressure to remain within the required threshold values;

- Minimize pressure swings to mitigate the potential impact on pipeline integrity.

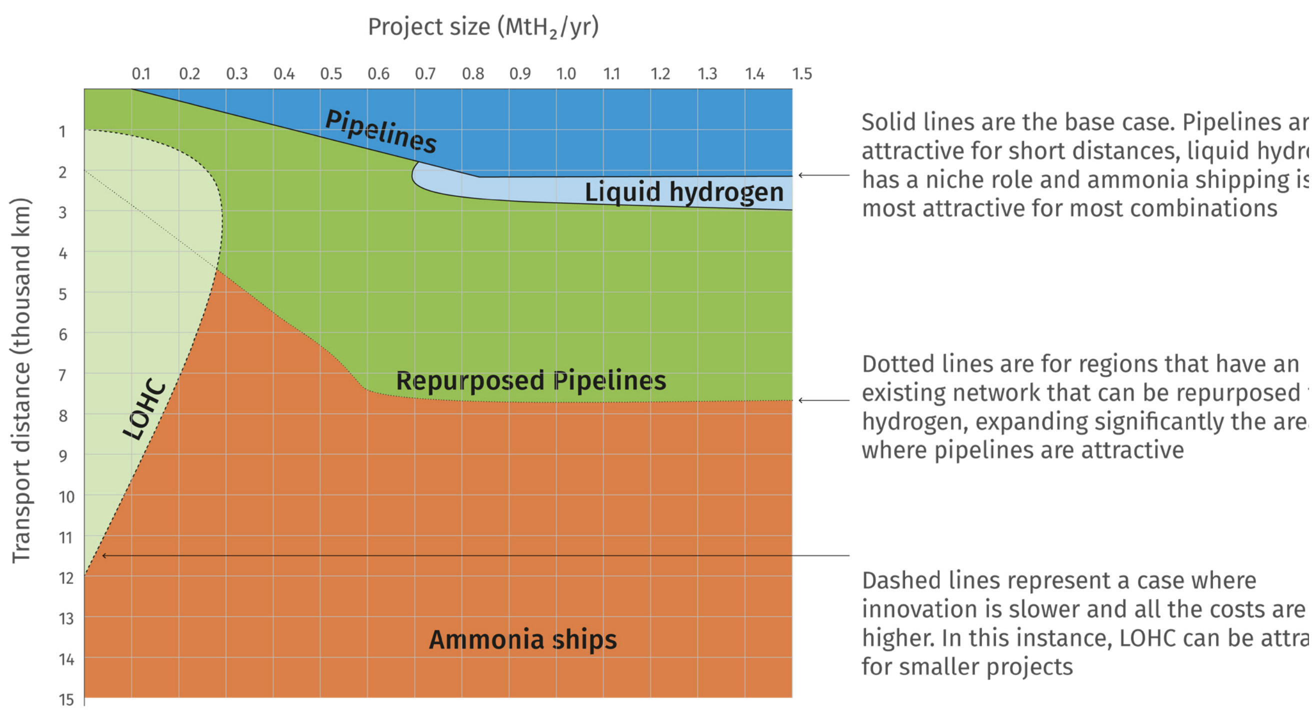
Authorities must consider certain formal and bureaucratic factors when contemplating the transition of an existing pipeline to a new commodity, for example establishing clear criteria to determine when a new operating approval is necessary, taking into account factors such as the concentration of hydrogen transported. Additionally, it is important to acknowledge that many current long-term transmission contracts are in effect for these pipelines. Governments must therefore devise strategies to amend these contracts if they intend to shift from natural gas to hydrogen.

When the repurposing of existing infrastructure for hydrogen transport is not technically feasible or when there is still demand for natural gas, **constructing new hydrogen pipelines alongside existing natural gas pipelines is an alternative strategy**. This offers several advantages as established right-of-way and existing siting permits can be capitalized, resulting in cost savings and shorter timelines for pipeline development. By using the same routes and infrastructure used by natural gas pipelines, the construction of new hydrogen pipelines can benefit from the groundwork already laid, reducing the need for extensive land acquisition and permitting processes. This approach provides a practical solution for integrating hydrogen into existing energy networks while maximizing efficiency and minimizing disruptions to the overall system (IEA, 2022c).

The use of onshore or offshore pipelines for cross-border trade is significantly limited by the availability of existing networks and the lead times required for dedicated pipeline construction. The planning and construction of a dedicated hydrogen pipeline depends on various factors, including bureaucratic efficiency and acceptance by the population directly affected. Currently, there are plans to transport GH2 from North Africa to Germany and other Central European countries through Italy, and from North Africa and the Iberian Peninsula to France. The Mediterranean Hydrogen Pipeline project H2Med aims to connect Portugal and Spain with France and Germany, supplying around 10 per cent of the EU's hydrogen demand by 2030 (Hydrogen Central, 2023).

The most feasible option for ramping up GH2 trade and transporting large amounts of hydrogen over long distances is maritime transport. While the pipeline option may be viable for certain regions, it is not practical for areas that have the greatest demand and are located outside the MENA region, namely Europe, Japan and the Republic of Korea. Sea vessels are the only realistic option for transporting large amounts of hydrogen from net GH2 exporters to net GH2 importers outside of pipeline range as depicted in Figure 5.1 and Figure 5.2. Major technical and economic challenges might impede the roll-out of a truly global hydrogen ecosystem until at least 2030.

Figure 5.1. Most cost-effective hydrogen transport pathway in 2050 as a function of project size and transport distance



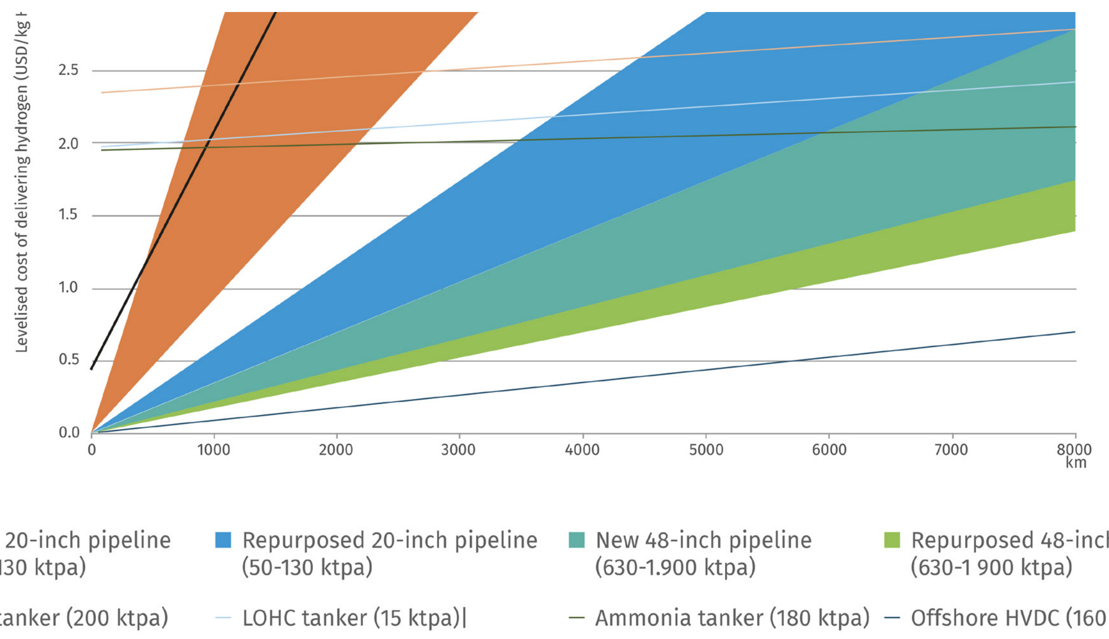
Source: IRENA, 2022c

5.1.2. GH2 carriers

Hydrogen can be transported via vessels using three main carriers: (i) liquefied hydrogen (LH2), (ii) ammonia (NH3), or (iii) LOHC. LOHCs chemically bind hydrogen to a carrier material and release it at the destination. As such, they require a higher number of landings—and thus ships—compared to ammonia. Regardless of carrier option, the transport and re-/conversion of/into hydrogen significantly increases the landed costs of hydrogen, more than doubling the cost of production (Roland Berger, 2021).

A 2021 study by Roland Berger predicts significant cost reductions across all carriers as the hydrogen transport market expands. The study highlights the potential for substantial improvements in LOHC technology due to scale effects and learning curves. Factors contributing to cost reduction include increased equipment production volumes, economies of scale for larger plants, advancements in materials, plant efficiency, and standardization for hydrogenation and dehydrogenation processes as well as in carrier substances. The full commercialization of carrier technologies is expected to lead to cost cuts in conversion and reconversion plants. Direct costs related to storage, transport and handling are significant. LOHC, with its operational advantage, is anticipated to leverage its cost advantages in complex and storage-intensive multimodal transport routes, as conversion and reconversion costs decrease significantly.

Figure 5.2. Cost of hydrogen delivery for various transport distances



Source: IEA, 2022c. IEA analysis based on data from Guidehouse (2021) and IAE (2016)

Notes: ktpa = kilotonnes per year; LH2 = liquefied hydrogen; LOHC = liquid organic hydrogen carrier. Includes conversion, export terminal, shipping, import terminal and reconversion costs for each carrier system (LH2, LOHC and ammonia). The import and export terminals include storage costs at the port. Pipelines refer to onshore transmission pipelines operating at ranges between 25% and 75% of their design capacity during 5 000 full load hours. Electricity transmission reflects the transmission of the electricity required to obtain 1 kg H2 in an electrolyser with a 69% efficiency located at the distance represented by the x-axis.

Ammonia's cost development path is distinct due to its well-established commercial synthesis process and trade, which limits the potential for cost reductions in conversion, storage and transport. However, considerable cost reductions can still be achieved through additional cracking and purification processes, along with decreased energy requirements (Roland Berger, 2021). Moreover, the existing ammonia transport infrastructure, particularly in ports and terminals, can be used and expanded. While the use of ammonia as a shipping fuel is not as technologically mature as ammonia transport itself, it has the potential to create additional demand and contribute to a decarbonization of the emission-intense shipping industry. However, caution is advised as the widespread use of ammonia as a shipping fuel may disrupt the global nitrogen cycle if not carefully regulated (Wolfram et al., 2022). On the other hand, green methanol can also serve as a shipping fuel, leveraging substantial existing port infrastructure without posing the same toxicity risks as ammonia. Despite being green, methanol still emits CO_2 when burned as a fuel. The expanded use of ammonia as a hydrogen carrier and fuel for shipping can have unintended consequences for the fertilizer supply chain, potentially slowing down the decarbonization of fertilizer production. Moreover, the current bottleneck in shipbuilding for ammonia transport poses a significant challenge that will take years to resolve.

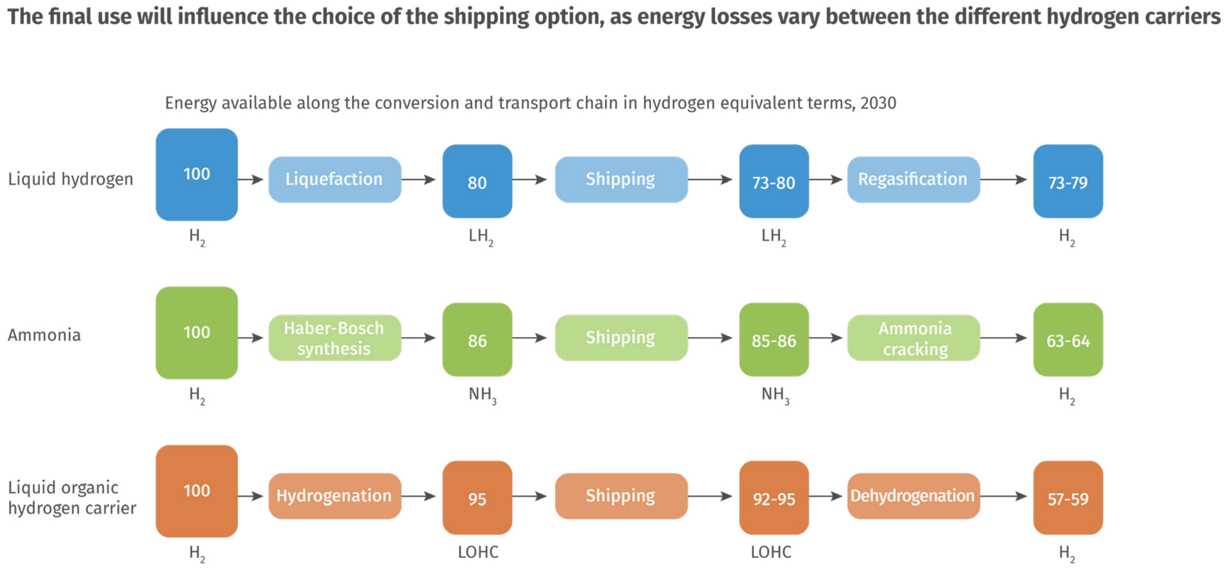
To secure green hydrogen for end-uses, trading green ammonia will need to undergo ammonia cracking to convert ammonia back to hydrogen at scale. This technology is still in its early stages and faces numerous challenges that need to be overcome before affordable, off-the-shelf cracking units can be manufactured. Alternatively, ammonia can be used directly as an energy vector, serving as a fuel without the need for cracking. Therefore, an export-focused strategy reliant on ammonia may not yield favourable results for many countries simultaneously.

Compared to LOHC and ammonia, the liquefaction of hydrogen is expected to be associated with lower costs and energy reductions due to the already widespread availability of the technology (Roland Berger, 2021). Additionally, considerable investment cost reductions for LH2 storage, transport and stationary storage are anticipated, as are improvements in boil-off losses.

Selecting the most suitable carrier depends on operational factors and cost considerations, as no single carrier is universally ideal for all transport scenarios. For instance, despite higher costs, LH2 may be preferred for high-purity hydrogen and when on-site reconversion is impractical. While ammonia is a cost-effective option for small-scale multimodal transport, safety regulations and increased costs may tip the scales in favour of LOHC. Integrating existing heat sources at the off-taker could enhance the viability of ammonia and LOHC, potentially reducing required temperatures. Ultimately, the best choice for a specific supply route must be determined on a case-by-case basis, taking individual circumstances into consideration.

It is anticipated that multiple technologies will coexist in the market during the ramp-up and scaling phase of hydrogen transport. The technology ultimately chosen depends on factors such as market uptake speed, potential for cost reduction, and the ability to provide a safe and user-friendly solution. This introduces significant uncertainty in the future of long-distance GH2 distribution and trade, including the risk of technological lock-in and stranded assets for carrier infrastructure, such as ports and converters. International coordination is crucial to ensure a clear path forward and prevent delays in infrastructure roll-out, especially with regard to GH2 trade (see Section 6.5). Policymakers should avoid reliance on just one mode of transport when planning export infrastructure, and instead opt for a mix of carrier technologies that leverage their respective strengths and that remain adaptable to future developments. Another cautious approach could involve expanding existing in-country trade infrastructure for ammonia, methanol or other GH2 products and its derivatives. The uncertainties surrounding GH2 transport infrastructure for trade emphasizes the need for a dual approach that includes a significant share of local GH2 use.

Figure 5.3. Energy losses for different energy carriers



Source: IEA, 2022c

Notes: LH2 = liquefied hydrogen; NH3 = ammonia; LOHC = liquid organic hydrogen carrier. Numbers show the remaining energy content of hydrogen along the supply chain relative to a starting value of 100, assuming that all energy needs of the steps would be covered by the hydrogen or hydrogen-derived fuel. The Haber-Bosch synthesis process includes energy consumption in the air separation unit. Boil-off losses from shipping are based on a distance of 8 000 km. For LH2, dashed areas represent energy being recovered by using the boil-off gases as shipping fuel, corresponding to the upper range numbers. For NHs and LOHC, the dashed area represents the energy requirements for one-way shipping. which are included in the lower range.

5.1.3. GH2 storage facilities

With the significant role hydrogen is expected to play in the energy system, the **importance of storage** cannot be overstated in ensuring hydrogen's reliability. Efficient storage solutions serve multiple purposes in this context:

1. They enable the **balancing of supply fluctuations** arising from electrolysers powered by variable renewable electricity, while also accommodating for seasonality in hydrogen demand.

2. Storage plays a crucial role in **providing energy security** by mitigating the impacts of supply disruptions caused by trade conflicts, unforeseen outages and natural disasters, ultimately reducing price volatility.

3. Storage at ports will also be needed when hydrogen's maritime transport takes off.

Demand for hydrogen storage differs from that for natural gas, which is primarily driven by seasonal demand for heating. Hydrogen demand is less influenced by seasonality, but the **significant fluctuations in electricity generation from variable renewables necessitate flexible hydrogen storage to not only effectively meet demand but to also minimize the need for excessive infrastructure capacity** (IEA, 2022c). There are two major methods for storing hydrogen: (i) physical, and (ii) chemical. The physical approach uses geological formations underground to store hydrogen in liquefied or compressed form, similar to natural gas. The chemical route involves conversion processes using liquid carriers such as ammonia, methane or LOHCs.

5.1.4. Just Transition dimension

The infrastructure construction phase of ports, pipelines and storage capacities provides temporary employment opportunities that are significant in nature. However, these investments are capital-intensive and require large-scale operations, making it difficult for new players to enter the market. As a result, foreign investments and imported technology tend to dominate these core activities in most developing countries. While the local workforce is involved in construction work, the potential for sustainable job creation lies in training, skills development and education to capture the technically more demanding maintenance and technician roles.

Building new infrastructure for GH2 entails land requirements which may cause disruptions to agricultural use and local food supply, displacement of populations, property devaluation and environmental degradation. It is therefore essential to develop holistic strategies that consider all dimensions of the GH2 transition. **Governments must prioritize the resilience and livelihoods of local communities when planning GH2 infrastructure for a just hydrogen transition.** While potential benefits in terms of employment and export revenues are significant, they should not come at too high a price, such as water and food security or social disruption. This is discussed in more detail in Section 3.3.3.

5.2. Regulating transport

Similar to GH2's industrial applications, its **distribution calls for comprehensive, clear and long-term regulations that facilitate planning, financing and safety.** This becomes even more critical for cross-border transport as it plays an essential role in creating a viable global GH2 market and in facilitating trade. It is therefore imperative to adopt standardized protocols for GH2 transmission and to promote international coordination to prevent distribution bottlenecks in both export and local value chains (see Section 6.5.2 for a discussion on standards and certification coordination at the global level).

Given the growing importance of GH2 infrastructure, governments must carefully evaluate their institutional requirements to effectively regulate these systems. This evaluation should consider the availability of institutional resources and explore the possibility of implementing new regulatory arrangements or authorities. Key policy areas to be addressed are:

- Adoption of technical standards and regulations;
- Adjustment of formal requirements such as approvals, permits, contracts, etc.;
- Implementation of risk assessment regimes for leaks and security;
- Reaching international agreements for cross-border transport.

The establishment and adoption of global standards for hydrogen transport across different carrier options is essential to ensure a secure, efficient and transparent environment for cross-national projects. This entails defining the requirements for product quality and safety and determining the environmental impact. Such market rules are urgently needed to facilitate the necessary investment in hydrogen transport infrastructure and carrier technologies. Early adopters that build large-scale hydrogen trade hubs and port- or industrial clusters will have the opportunity to shape the standards that will define the future of GH2 distribution. These standards will also encourage importing countries to diversify their hydrogen sources, creating export opportunities for producer countries located far from demand centres.

To maximize GH2's decarbonization benefits and prevent negative climate impacts in the short term (see Box 5.1), the lessons learned from the ongoing methane leakage issue must be applied. **A well-regulated hydrogen value chain can effectively mitigate the risks of leakage.** Immediate action must be taken to obtain the necessary scientific evidence and tools that will support the implementation of effective policies and regulations. These measures should be implemented at the global level and require multilateral coordination (see Chapter 6 for further details).

Box 5.1. Hydrogen as an indirect GHG

While hydrogen itself is not a direct GHG and does not produce GHG emissions when combusted as a fuel, its release into the atmosphere can still have climate impacts. This is because hydrogen interacts with other gases and chemicals, affecting the concentrations of methane, ozone and water vapour. In fact, hydrogen has a 100-year global warming potential that is around 11 times higher than carbon dioxide (Warwick et al., 2022). These impacts are not associated with the direct use of hydrogen in industrial or other applications, but rather with potential leakage during the transport and handling processes. Due to its small molecule size, high diffusivity and low viscosity, hydrogen can leak throughout the entire value chain. The lack of comprehensive data on hydrogen leakage rates poses challenges in assessing the potential risks and impacts. Currently, empirical measurements for on-site hydrogen production and industrial usage focus primarily on operational safety, with hydrogen leak detectors typically operating above the threshold for hydrogen gas flammability. Furthermore, data on the extent of hydrogen leakage in pipelines and compressors are limited. Research to evaluate how leakage levels may change when repurposing natural gas infrastructure for hydrogen must be carried out. Additionally, as hydrogen expands into new applications, the development of international trade and infrastructure will be necessary. Operations involving the loading and unloading of pressurized or liquefied hydrogen in trucks, ships or storage tanks present notable risks in terms of potential leakage.

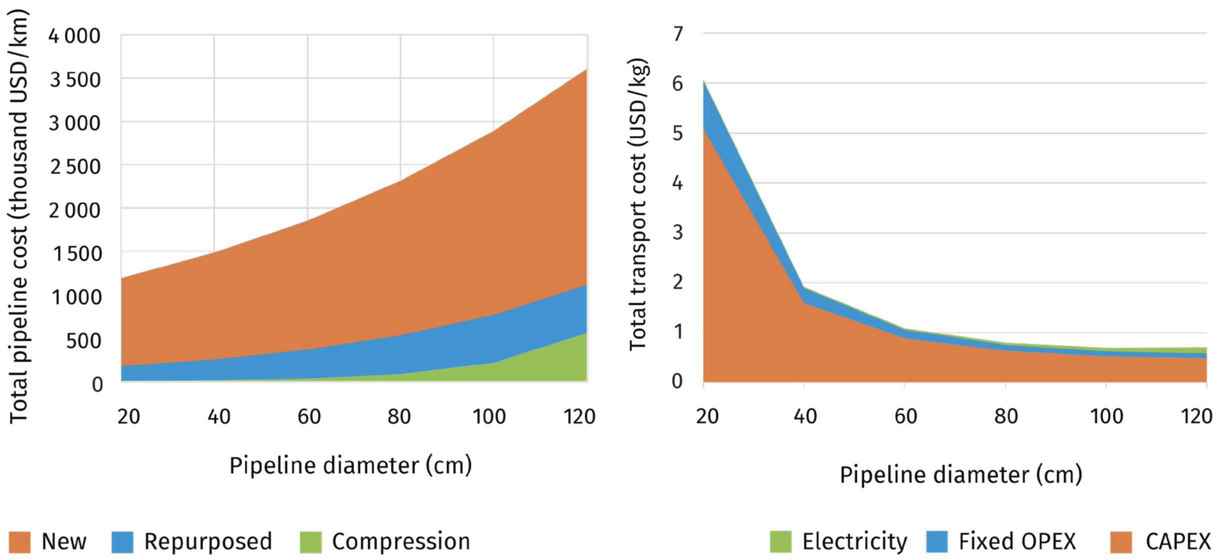
5.3. Infrastructure financing

As outlined in Section 5.1, there has been a lack of focus on hydrogen transport infrastructure development compared to its production and end-uses. **At present, only around 10 per cent of proposed hydrogen investments are directed towards infrastructure, highlighting an investment gap of about 85 per cent to the estimated USD 200 billion required by 2030** (Hydrogen Council and McKinsey and Company, 2022). Government should prioritize infrastructure investment to bridge this gap and initiate the development of this foundational element of the GH2 value chain. For a meaningful and large-scale transition, however, it is essential to also simultaneously leverage private sector financing, expertise and priority-setting. The main challenge lies in securing investments for the retrofitting and repurposing of existing natural gas networks as well as establishing new dedicated hydrogen infrastructure. Policymakers have a range of options to support this endeavour, but the **choice of intervention should be based on the existing grid's stage of development.**

As mentioned, to facilitate the development of GH2, existing natural gas networks will need to be retrofitted and new pipelines constructed. Selected projects should focus on showcasing successful transitions from natural gas to dedicated hydrogen assets. The assessment process for such projects will play an important role in ensuring that the infrastructure is designed to progressively increase the share of GH2 in the pipelines and in the overall grid. By the end of the transition period, this will require dedicated hydrogen assets for transmission, storage and distribution (Hydrogen Council, 2021).

Repurposing existing gas grids offers significant financial benefits compared to building entirely new infrastructure. Figure 5.4 illustrates that repurposing natural gas pipelines for hydrogen use can reduce the required CAPEX by 65 per cent to 94 per cent relative to new, purpose-built hydrogen pipelines (IRENA, 2022c). This range depends on the pipeline's diameter size, with the narrowest type (500 mm) showing the highest difference in price, especially when considering compression. While not covered in this report, and important consideration for investment planning is the expected lifetime of a repurposed pipeline relative to a new one, i.e. the capital cost per year of operation. Public financing will play a crucial role in funding anchor projects and reducing transport costs in support of the GH2 market's development. De-risking measures can also attract private investment in midstream hydrogen projects (Hydrogen Council, 2021). These measures may include loans, grants and debt guarantees, as outlined in more detail in Section 4.2.

Figure 5.4. Capital cost of a hydrogen pipeline (left), & total transport cost (right) by cost component



Notes: Right figure is for 5 000 km.

Source: IRENA, 2022c

Public-private partnerships (PPPs) offer a promising avenue for increasing infrastructure investments. Projects with substantial investment requirements, such as commercial-scale GH2 export and import infrastructure, can benefit from PPPs while GH2 finance mechanisms and business plans mature. Such partnerships involve a combination of direct public investment and multi-stage competitions for awarding contracts. For example, the government can contribute necessary land and permits, while capital investments are shared, and the private enterprise provides technical expertise. **The project is jointly managed, and risks and returns are shared between the government and the private enterprise.** To mitigate risk, a gradual approach that starts with funding smaller projects can provide reassurance to investors (IEA, 2019). Subsequent projects can then leverage the knowledge and experience gained from earlier projects, while raising awareness of public financing and partnership options. The coordination challenges that PPPs often face can be addressed through clearly defined responsibilities starting in the planning stage (Cammeraat et al., 2022).

Box 5.2. Kochi Green Hydrogen (KGH2) Hub project

The Kochi Green Hydrogen (KGH2) Hub project is an ambitious initiative led by the India Hydrogen Alliance (IH2A) and the regional Government of Kerala. It aims to establish a large-scale green hydrogen hub equipped with a 150 MW electrolyser and comprehensive storage and transport infrastructure, involving a total investment of USD 575 million. The project will be developed through a public-private project consortia structure, with participation from industry, state-owned enterprises, government and multilateral funding agencies, and will be governed by a two-tier KGH2 governance structure, consisting of a public-private advisory group and project consortia structures (India Hydrogen Alliance, 2022).

Constructing new dedicated infrastructure is essential for facilitating the growth of GH2 as a clean energy carrier and connecting emerging areas of demand and supply. **By linking industrial clusters and GH2 hubs with export infrastructure, there is potential for a profitable business model that can attract private investment** and international financing from importing countries, which will facilitate trade-related transport development. **Governments can provide incentives for private sector investment in large infrastructure projects by guaranteeing returns through a regulated asset base model** (RAB). Such models guarantee returns for investors in network utilities by providing principles for determining price caps. They allow for both private and public ownership of the infrastructure assets. The RAB primarily evaluates the value of assets used for regulated functions and serves as an accounting measure that reflects past investments in network infrastructure. Through current cost accounting, the RAB considers a realistic replacement value when estimating the present value of long-lasting infrastructure (Makovšek and Veryard, 2016). The regulated returns could, for example, use pricing based on improving performance over time. Introducing price ceilings and floors may help foster efficiency further. Such a RAB can remain in place even when the GH2 market approaches maturity, ensuring that infrastructure providers can operate competitively and efficiently (Hydrogen Council, 2021).

As the GH2 market matures, the importance of ancillary services such as a buffering and storage will increase, enabling PtX and making hydrogen a flexible energy vector. The associated infrastructure will play a key role in the efficient distribution of hydrogen along the value chain, including grid operation, conversion for export and feedstock reserves for industry. Ultimately, this can lead to a profitable business case, with revenues replacing financial support policies. However, **before bankable offtake schemes become a reality, governments should incentivize hydrogen storage construction through public storage procurement.** This can be achieved by issuing tenders or contracts to private companies for the design, construction and operation of storage facilities. The procurement process should include specific requirements for storage capacity, safety standards and environmental considerations. The government should also consider strategic placement of storage facilities to facilitate GH2 transport and distribution to relevant end-users, industries and export markets. By providing financial support or incentives for the establishment of storage facilities, governments can address one of the key challenges in scaling up hydrogen take-up, namely the ability to effectively store and distribute hydrogen.

6. Options for international cooperation to support national policymaking

Countries in the Global North have a significant advantage in terms of financial and human resources as regards the development of hydrogen policies compared to countries in the Global South. Figure 1.3 shows that out of over 45 NHS published as of June 2023, 60 per cent were from developed countries. Policymakers in countries in the Global South face resource limitations, including a lack of qualified personnel and competing priorities for other, more pressing issues. International collaboration is crucial for addressing these challenges and accelerating the development of a comprehensive hydrogen policy framework in many countries. This can be achieved through co-financing the creation of a policy framework, knowledge sharing, intergovernmental MoU, policy-supporting financing from the Global North to the Global South and policies for trading green products. By leveraging international cooperation, countries can bridge gaps and ensure a more inclusive and sustainable hydrogen transition.

6.1. Co-financing the development of a policy framework

Developing a policy framework for hydrogen is resource-intensive and requires a qualified and experienced team. Hence, **identifying solutions to co-finance the development of a policy framework** can accelerate its creation. Examples of co-financers of strategy and roadmap development include the German Agency for International Cooperation (GIZ), the United States Agency for International Development (USAID) and various multilateral development banks (MDBs). GIZ has supported the development of national hydrogen strategies in Chile, Kenya and Namibia, for example, and is active in many other countries. USAID supports research, capacity development and policymaking in the field of renewable energy and hydrogen through its Scaling Up Renewable Energy (SURE) programme. During the period 2017–2022, over 5,000 individuals worldwide were trained in clean energy (USAID, 2022). USAID has also assessed the hydrogen potential of countries such as India and Mauritania. The national hydrogen strategies of Colombia, Costa Rica, Panama, Paraguay, Trinidad and Tobago and Uruguay were developed with the support of the Inter-American Development Bank. The European Bank for Reconstruction and Development (EBRD) is assisting Azerbaijan and Egypt in assessing their hydrogen potential (Makhmudova, 2023; Zgheib, 2022).

To accelerate global GH2 adoption, the necessary policy and legal frameworks need to be developed, international standards coordinated and R&D efforts on GH2 technologies supported. Recognizing this need and to encourage GH2 use to decarbonize industry and promote low-carbon industrial development around the world, UNIDO launched its Global Programme for Green Hydrogen in Industry (GPHI) in July 2021 (UNIDO, 2023b). The GPHI focuses on technical cooperation for developing countries, aiming to strengthen local GH2 policies, enhance local financial, technical and knowledge capacities and to develop local pilot projects.

The United Nations Economic Commission for Europe (UNECE), with support from donor countries, has conducted assessments on the hydrogen potential of countries in Central Asia and the Caspian region (UNECE, 2023). In addition, the Asian Development Bank (ADB) collaborated with Georgia to launch a project in 2022 that aims to develop a policy, strategy and regulatory framework for green hydrogen development with private sector participation (ADB, 2022). The World Bank's Hydrogen for Development (H4D) Partnership aims to bring together hydrogen stakeholders, identify synergies, foster capacity development, regulatory solutions, business models and technologies to facilitate the roll-out of low-carbon hydrogen in developing countries. As part of this effort, the ESMAP Green Hydrogen Support Program supports governments and the private sector by providing investments and regulatory solutions and developing quality project pipelines in Brazil, Chile, India, Mauritania and Namibia, amongst others.

Prioritizing funding for research and the development of guidelines for policymakers from international organizations such as IRENA, UNIDO, IPHE, OECD and UNECE is crucial in the emerging field of hydrogen. These institutions' projects primarily focus on research on hydrogen policy and technologies, resulting in the production of high-quality reports and guidelines that are freely available to all interested parties, including policymakers in developing countries. IRENA's first report on the role of renewable hydrogen was published in 2018 with the support of Japan (IRENA, 2018). In the past five years, several dozen reports have been made available to policymakers to facilitate their entry into the hydrogen industry.

6.2. Multilateral cooperation in science, technology and innovation to accelerate global GH2 production and application

There is a clear argument in favour of **multilateral cooperation in science, technology and innovation to address the challenge of GH2 use** (Stamm et al., 2012). The rapid scaling up of global GH2 as outlined in international strategy documents necessitates the establishment of a new complex and expansive technical system within a very short timeframe. Historically, the development of large systems such as the power system, railroad and telecommunications took several decades, involving experimentation and the identification of best practices. In the context of GH2, a global system must be established within a very short time, starting with the large-scale production of a green commodity and the logistics related to the establishment of a global trade framework for substances that are difficult to handle (i.e. hydrogen and its derivatives) as well as applying this framework in different offtake industries. Each step of the supply chain presents a range of technological and systemic uncertainties that must be addressed. To navigate these uncertainties and enable stakeholders to make informed policy decisions, substantial R&D efforts and knowledge dissemination are crucial. This will ensure that the most recent information and knowledge guide policymaking at every stage of the GH2 value chain.

The development of GH2 presents an opportunity for many industrializing countries to gain a competitive edge and advance their economies. Certain challenges must, however, be addressed at the multilateral level, such as the challenge of maximizing hydrogen's decarbonization potential while minimizing any adverse climate impacts in the short term (see Box 5.1). As already mentioned, by establishing **a well-regulated hydrogen value chain, the risks of leakages can be effectively mitigated.** Urgent actions are needed to develop the necessary scientific evidence and tools that will facilitate the implementation of effective policies and regulations. Some key points for consideration include:

- Support research endeavours aimed at advancing knowledge about hydrogen's potential global warming effects, which still harbour some uncertainties. This includes the development of climate models capable of incorporating the unique characteristics of hydrogen leakage and facilitating a comprehensive assessment of its environmental impact.

- Invest in research initiatives to collect evidence and minimize uncertainties related to the risks associated with hydrogen leakage across the entire value chain, with specific emphasis on repurposed natural gas infrastructure.

- Identify effective strategies and best practices to address hydrogen leakage, encompassing technical solutions for the detection and repair of leaks.

- Implement robust methodologies for measuring, reporting and verifying hydrogen leakage, establishing standardized protocols to ensuring accuracy and consistency.

6.3. Knowledge sharing: Dialogue and capacity development

Despite the vast amount of publicly available resources on hydrogen policy and technologies, many technical and systemic uncertainties prevail. In addition, knowledge about hydrogen among policymakers responsible for developing and implementing hydrogen policy in their countries is unevenly distributed. **The dissemination of knowledge in all its possible forms is therefore crucial.**

Knowledge dissemination is essential to effectively address the disparities between the Global North and the Global South. The Global North, which has far more experience and financial resources, can significantly contribute to the hydrogen industry's development. The Global South, on the other hand, possesses in-depth knowledge of the local peculiarities that differ considerably from conditions in the Global North. To bridge these gaps, it is imperative to facilitate knowledge sharing at multiple levels, ranging from ministers to frontline policy developers. By fostering collaboration and information exchange, policymakers can gain a comprehensive understanding of the GH2 industry and make informed decisions that benefit all. One such example is the International Hydrogen Energy Center (IHEC), which was established by UNIDO with China's support in Beijing in 2021. It aims to develop capacity, disseminate knowledge and advance research in hydrogen in developing countries (UNIDO, 2021).

In addition to collaborative research, the most commonly used formats for knowledge sharing include educational initiatives (such as funding internships, MSc and PhD programmes, capacity development trainings, etc.) and forums (conferences, dialogues, etc.). To date, only few educational programmes exist that focus explicitly on cultivating substantial competencies in GH2. One notable case is the collaboration between West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), RWTH and Forschungszentrum Jülich (see Box 6.1).

Capacity development events are the most common form of knowledge dissemination in the field of hydrogen policy. Such events, which can be conducted both online and in-person, are already being organized by H2Diplo (GIZ), the International PtX Hub (GIZ), USAID-SURE, IRENA, UNIDO and many others. The primary objective of such events is to provide policymakers with a comprehensive overview of the hydrogen industry within a short timeframe (usually a few hours or days), enabling them to effectively formulate national hydrogen policies. However, the volume of content, its complexity, multidisciplinary nature, cross-sectoral aspects and language barriers pose significant challenges to upskilling participants. To foster successful educational initiatives, it is crucial to integrate a variety of approaches and methodologies. This includes incorporating both theoretical and practical assignments, encouraging both collaborative group work and individual work, brainstorming sessions, gamification, personalized learning pathways with dedicated support from tutors and professors, and leveraging modern educational technologies. While these practices have been effectively implemented by international business schools in executive training programmes, their use in the upskilling of policymakers is still relatively uncommon.

Box 6.1. International Master's Programme in Energy and Green Hydrogen

The West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), under the sponsorship of the German Federal Ministry of Education and Research (BMBF), has initiated an International Master's Programme in Energy and Green Hydrogen, an interdisciplinary study programme to address the energy challenges of adaptation and resilience to Climate Change in West Africa. WASCAL is a fully West African international organization with a focus on academic and transdisciplinary research, developing graduate-level scientific capacity and serving policymakers in West Africa with science-based recommendations on adaptation to climate change impacts and land use management. The master's programme offers expertise in hydrogen at Forschungszentrum Jülich and RWTH Aachen University, both located in Germany.

Source: WASCAL, Jülich and Aachen

Conferences and forums on hydrogen policy have gained significant traction and have become more diverse, targeting policymakers at different levels and regions. These events serve as platforms for policymakers to exchange ideas and insights on hydrogen policy. The first high-level Hydrogen Energy Ministerial Meeting, primarily aimed at policymakers, was held in Japan in 2018, with the participation of 300 representatives from 21 countries, and has taken place annually since (Ministry of Economy, Trade and Industry, 2018). In separate side events, hydrogen policy has become part of larger international forums on climate policy and energy transition, such as the Conference of Parties (COP) by the United Nations Framework Convention on Climate Change (UNFCCC), the Clean Energy Ministerial (CEM), IRENA Assembly and Collaborative Framework on Green Hydrogen, G20 and many others. Dialogues between policymakers can also take place bilaterally. For example, the Federal Ministry of Economic Cooperation and Development and the Federal Ministry for Economic Affairs and Climate Action of Germany organize green hydrogen symposiums, forums, dialogues and capacity development events in partner countries, including Kenya, Nigeria, Kazakhstan, Oman, Namibia, Saudi Arabia, Ethiopia and Angola. Examples of high-level regional forums that bring together policymakers and the private sector include the European Hydrogen Week (held since 2020), the World Hydrogen MENA (held since 2021) and the Africa Green Hydrogen Forum (first held in 2022).

6.4. Policy to support financing from the Global North to the Global South

The financing of the clean energy transition, particularly in the Global South, is a critical aspect of the hydrogen supply chain. It is imperative to address the broader challenge of financing the transition to a 1.5°C pathway. The most viable approach involves directing financing towards decarbonization efforts in countries where these are more cost-effective and where there are abundant opportunities for renewable energy development, namely in the Global South. Countries in the Global South possess immense untapped potential for renewable energy sources, making it economically feasible to invest in their clean energy transition. To achieve this scenario, countries in the Global South will require a comprehensive overhaul of their economies, with annual investment requirements ranging from 2 per cent to 4 per cent of national GDP (GCA Collaborative, 2022). However, limited resources and fragmented financial systems prevent low- and middle-income countries in the Global South from achieving the necessary investment levels without a substantial increase in financing from the Global North. The challenge thus lies in creating a political and regulatory framework at the international level that fosters mutual trust and attracts investments, primarily from the private sector.

There is a clear bias towards the Global North when it comes to renewable energy financing. While some developing countries such as Brazil, Chile and India have succeeded in attracting substantial investments in renewable energy, the majority of developing and emerging countries has received a disproportionately lower share of total global investments in renewables. This discrepancy is particularly evident for countries classified as "least developed", which received less than 1 per cent of total investments in renewable energy between 2013 and 2020 (IRENA, 2023a). At the 15th Conference of Parties (COP15) of the UNFCCC in Copenhagen in 2009, developed countries committed to the collective goal of mobilizing USD 100 billion annually for the Global South. As revealed at COP26 in Glasgow in 2021, developed countries had not fulfilled their pledge. To put this into perspective, the financing of projects related to GH2 production, transport and use in emerging markets and developing countries would require an annual average investment ranging from USD 250 billion to USD 500 billion between now and 2050 (Gielen et al., 2023).

Developing countries face significant challenges in narrowing the cost gap between GH2 and its alternatives (such as grey hydrogen in industry and fossil fuels in the energy sector) and establishing the necessary GH2 infrastructure. To address this gap, international climate financing must be markedly increased. Members of the research initiative Global Climate Alliance (GCA), which consists of institutions and individuals from Europe and India, propose establishing a Global Climate Alliance with broad participation from key countries in both the Global North and South (primarily the G20), based on the principle of Common but Differentiated Responsibilities (CBDR). Within this alliance, legally binding commitments could be announced and monitored, not only in terms of reducing GHG emissions but also in terms of contributing funds to a Climate Financing Pool and facilitating technology transfers. These commitments could be overseen by an existing global institution such as the World Bank or the International Monetary Fund. Financing could be generated through various mechanisms, including carbon tax programmes, the redirection of special drawing rights, or official development assistance (GCA Collaborative, 2022). Until such a large-scale alliance is established, policymakers can aim to reduce the risks of GH2 production projects by lowering the cost of capital (including through blended financing), combining public investments with substantial private investments, and engaging development finance institutions (DFIs) and MDBs. The establishment of a transparent and predictable long-term regulatory framework, as discussed in Chapter 4, plays a crucial role in this process.

6.5. International coordination for hydrogen trade routes

At present, the hydrogen industry operates primarily at the local level, with production and consumption taking place within the given facility. The transport of hydrogen over long distances remains a significant hurdle due to logistical complexities and high costs. Once these challenges are resolved, however, the possibility of establishing global trade routes for hydrogen could become a reality. In 2022, global hydrogen imports were valued at approximately USD 300 million. The United States and The Netherlands were the leading importers of hydrogen in 2021, each accounting for around one-third of global hydrogen imports. The top 10 import markets represented nearly 90 per cent of global hydrogen trade. Canada and Belgium were the top exporters of hydrogen, supplying the United States and The Netherlands, respectively (IRENA and WTO, 2023).

Global hydrogen trade, although growing, is still relatively small compared to other commodities such as ammonia and methanol, which reached USD 17.5 billion and USD 14.1 billion in imports in 2022, respectively. The trade landscape for ammonia is more global compared to hydrogen, with the United States and India being the top destination markets for ammonia in 2021. Other economies such as Morocco, the Republic of Korea, China, Taiwan (Republic of China), Thailand, Brazil and Chile are also major import markets for ammonia. The top five suppliers of ammonia in 2021 were Trinidad and Tobago, the Russian Federation, Indonesia, Saudi Arabia and Algeria (WTO/IRENA, 2023). China stands out as the largest market for methanol, accounting for 25 per cent of global methanol imports, while other significant import markets including India, The Netherlands, the United States, the Republic of Korea and Japan have similar import shares, ranging from 5 per cent to 7 per cent in 2021. The primary methanol suppliers are natural gas producers, including Trinidad and Tobago, Saudi Arabia, Oman, the United Arab Emirates, the United States and the Russian Federation (IRENA and WTO, 2023).

Hydrogen and its derivatives have the potential of becoming globally traded commodities in the future. The emergence of green variants opens up new avenues for transporting solar and other renewables across borders, effectively enabling the transport of "sunshine". This transformative capability holds the promise of fundamentally reshaping the existing trade landscape of hydrogen, ammonia and methanol. The primary catalyst for this transformation would be the price of the supplied commodity, with the cost of electricity serving as a key determinant in GH2 production.

GH2 is expected to be most economically produced in regions that possess a favourable combination of abundant renewable resources, available land, access to water and efficient energy transport and export capabilities to meet the demand of major centres. The current MoU with developing countries (see Section 6.5.1) highlight this trend. They boast ample renewable energy resources, exporting their locally produced commodities to countries in the Global North. The International Hydrogen Trade Forum, coordinated by UNIDO, was launched in July 2023, and has further amplified efforts to accelerate international hydrogen trade. It brings together Australia, Brazil, Canada, Chile, Germany, Japan, Saudi Arabia, the Republic of Korea, The Netherlands, United Arab Emirates, United Kingdom, United States, Uruguay and the European Commission on behalf of the EU to accelerate international GH2 trade. Its primary objective is to provide a dedicated platform to foster dialogue between the governments of importing and exporting countries. From this starting point, more can and should be done, including intensified efforts in elaborating international standardization, the creation of trade corridors and the development of policies for favourable trade of green products.

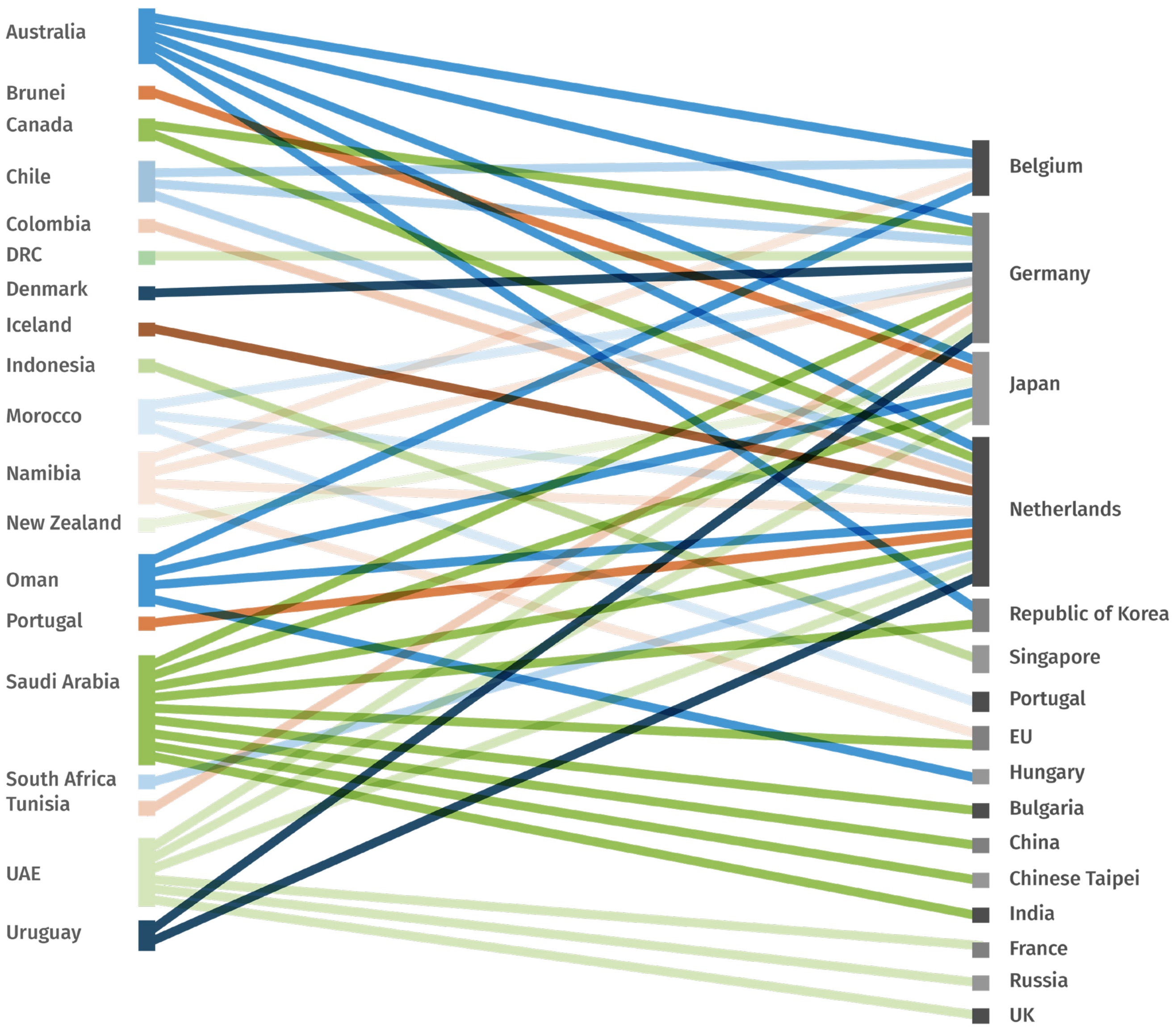
6.5.1. Intergovernmental Memoranda of Understanding

Many countries have established a **Memorandum of Understanding (MoU), Joint Declarations of Intent or other forms of partnerships to manifest their intentions to collaborate** in the clean energy and hydrogen industry. While MoU or partnership agreements may typically lack substantive obligations to detail the specific agenda of cooperation, the act of signing an MoU or similar agreement is significant in providing government and ministry officials with an endorsement for future work. Thus, while a MoU in and of itself is not crucial for initiating physical hydrogen or technology trade between countries, initiating such cooperation without one can be more challenging.

Based on the map of existing MoU, the EU and East Asia remain key import nodes on the network, as depicted in Figure 6.1. Over the past years, several new MoU have been concluded with countries in the Global South, including MENA, sub-Saharan Africa and Latin America.

Bilateral agreements can evolve into multilateral agreements over time. For example, Panama is planning to establish an intergovernmental organization to facilitate international trade of GH2 and its derivatives (Argus, 2023). Regional cooperation among neighbouring countries rather than mere bilateral agreements between importers and exporters may unlock opportunities to identify common approaches to overcoming barriers in hydrogen development and application, such as standardization, certification, logistics, supply chain, critical minerals, etc.

Figure 6.1. Existing bilateral MoU as of October 2023



6.5.2. International standards and certification

The international community has made progress in developing standards for hydrogen emissions, safety and operations. While ISO and UNIDO are joining forces to develop international standards in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen, there is still plenty of work that needs to be done to finalize the standards, especially in the areas of safety, operations and leakage (see Section 5.2) (IEA et al., 2023; ISO, 2022). Developing countries must actively engage in this process to ensure they can benefit from the global GH2 market. These benefits include access to the global GH2 market, attracting investments and partnerships by demonstrating that they are "hydrogen-ready", facilitating technology transfer, building technical capacity, reducing trade barriers, and shaping the development of standards to align with their unique needs.

Developing countries willing to invest in GH2 should actively monitor the progress of international standards development and at the same time participate in international standard setting. Developing countries can benefit from the work and resources of existing international organizations and initiatives, such as UNIDO and International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), to accelerate their engagement in setting hydrogen standards and certification. Developing countries should furthermore invest in building the necessary technical capacity to verify compliance with international hydrogen standards to ensure the long-term stability of hydrogen projects. This can be achieved through training, workshops and technical assistance programmes. UNIDO's activities to raise awareness and involve developing countries in international standards development can be particularly beneficial in this regard. Inclusivity in international standard-setting processes ensure that all voices are heard, and that countries' specific needs are considered in the development of standards.

In addition, developing countries should closely monitor GH2 certification scheme developments in Global North countries and advocate for alignment of methodologies for such certification and for the interoperability of certification systems. Currently, the three major certification systems (EU, United Kingdom and United States) have very different characteristics. The different approaches to the certification schemes (in terms of criteria, scope and methodologies) that are currently being implemented by different countries suggest that greater coordination is needed to prevent diverse accounting methodologies from becoming a barrier to the creation of a global GH2 market (IEA et al., 2023).

The lack of standardized certification methodologies can create obstacles to cross-border GH2 trade and hinder international cooperation, risking locking-in suppliers to a single off-taker and restricting trade to bilateral agreements. By promoting consistency and harmonization, developing countries can ensure their GH2 production finds a larger set of potential buyers. This will facilitate their market access and increase their investment attractiveness with risk mitigation.

6.5.3. International collaboration for trade corridors

International coordination to create early GH2 trade corridors is a crucial step in the hydrogen industry's transition. This collaboration ensures the establishment of a clear and defined path forward and may help prevent delays in GH2 infrastructure roll-out. By fostering international partnerships, such as the International Hydrogen Trade Forum (see Section 6.5), countries can pool their resources and share knowledge to accelerate the development and deployment of GH2 infrastructure. This not only speeds up the transition to clean energy, but also mitigates the risks of isolated, fragmented and competitive efforts. A successful energy transition requires the identification of best routes, i.e. "no-regret" options in which to invest as soon as possible. Moreover, international collaboration helps establish common standards and certifications for GH2, promoting transparency, trust and efficiency in cross-border trade (see Section 6.5.2). Consistent standards facilitate the interoperability of GH2 systems and technologies, enabling different countries to seamlessly engage in energy exchanges. Creating GH2 trade corridors calls for agreements and investments in infrastructure, including pipelines, storage facilities and transport methods. These corridors can help developing and emerging economies access the necessary infrastructure to support their nascent GH2 industry.

6.5.4. International collaboration for trading green products

Apart from GH2 and its derivatives, developing countries should also consider entering into the production of green products, such as green steel and green fertilizers. In this context, **unified approaches to green financing, together with green product standards will enhance the bankability of hydrogen projects**. The taxonomy of green finance and reporting provides consistency and transparency for climate investments, and aligning it globally will unlock financing opportunities. Green product standards, such as for steel or other products derived from GH2, will enable the creation of high-value industrial clusters in countries from the Global South, reducing the cost gap between "grey" and "green" products (for more details, see Section 4.3). Oman, the UAE and Mauritania, for example, are considering such a strategy (Gielen et al., 2023). However, reaching consensus on unified and standardized approaches will be challenging and requires fundamental changes in countries' collaborative efforts to address the climate crisis. In recent years, countries from the Global North (primarily the EU) have started implementing new international trade regulation mechanisms based on carbon footprint accounting. These mechanisms are aimed at preventing carbon leakage and safeguarding the competitiveness of local suppliers amidst varying national carbon regulation conditions. The first of such mechanisms is the EU's CBAM, which started its first phase in October 2023.

Box 6.2. EU's Carbon Border Adjustment Mechanism (CBAM)

The European Union's CBAM is a tool designed to address carbon leakage concerns and promote cleaner industrial production both within the EU and in non-EU countries. It is an import tax designed to ensure that the carbon price of imported goods is equivalent to that of domestically produced goods, thereby aligning with the EU's climate objectives and preventing the undermining of its environmental efforts. By introducing a carbon price on imports, the CBAM aims to encourage the adoption of cleaner production methods worldwide and to contribute to the EU's ambitious climate targets.

The CBAM initially targets carbon-intensive imports such as cement, iron and steel, aluminium, fertilizers and electricity, aiming to capture more than 50 per cent of emissions in the covered sectors. CBAM will be gradually phased in over time to allow for a predictable and proportionate transition for businesses. During the transitional period, which started in October 2023, importers of goods within the scope of the new rules will only have to report GHG emissions that are embedded in their imports (direct and indirect emissions), without making any financial payments or adjustments. Once the permanent system enters into force in January 2026, importers will need to annually declare the quantity of goods imported into the EU in the preceding year and their embedded GHG, and fulfil the import tax.

Source: European Commission, 2023

CBAM has led other Global North countries, including the United States, United Kingdom, Canada, the Republic of Korea and Japan, to consider implementing similar regulatory measures. In the future, this may also extend to China and South Africa (Adnett, 2023; Byers, 2021; Deloitte, 2022). In this context, it remains unclear whether a combination of diverse national counterparts to CBAM would be the optimal mechanism for stimulating global decarbonization and optimizing financing. On the one hand, they are designed to achieve this goal, as producers of green products within countries would gain competitive advantages over "non-green" imports. On the other hand, the full-scale implementation of these mechanisms with tracking and certification may take years, and unintended consequences such as barriers to competition, technology transfers and the redirection of carbon-intensive products to other markets could arise.

Policy Sheets

Clear policy direction

Policies to support enabling conditions for project inception:
Signal stability and clear guidelines to minimize risk for businesses and investors

1 National hydrogen strategy or roadmap

Objective	• As part of a country's decarbonization strategies, define the role green hydrogen should play in its future growth. • Adopt a long-term vision for green hydrogen value chain development through a participatory approach involving both the public and private sector, as well as civil society. • Present a clear strategy with defined commitments to green hydrogen production targets and green hydrogen-based industrialization.						
Key actions	• Operationalize long-term goals by breaking down the vision into milestones, translating them into binding short-term targets for advancing green hydrogen deployment. • Ensure alignment with existing industrial and energy strategies and other relevant policies and adopt a cross-sectoral approach to promote synergies and spillovers along the green hydrogen supply and value chain. • Describe future regulations and support measures to attract strategic investors, especially those already active in the renewable energy market. • Include hydrogen infrastructure considerations from the outset, especially related to storage and transport solutions. • Define governance mechanisms and/or describe the role of government bodies (e.g. a national inter-ministerial hydrogen council). • Identify, plan for and actively make use of co-benefits.						
Policy tools/ instruments	• **Green hydrogen policy document** – National Hydrogen Strategy or Roadmap.						
Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓	✓	✓	✓	✓	✓
Aspects to be considered	• Conduct assessments of local production, domestic use and export potential as the basis for defining government goals, strategies and initiatives for the advancement of green hydrogen. • Incorporate renewables in the energy transition agenda by considering factors such as the renewable energy production capacity, the existing infrastructure, technological capabilities, etc. Adjust targets (short-, medium- and long-term) to include hydrogen production. • Assess local conditions for retrofitting and repurposing the gas grid for hydrogen use and/or for building new dedicated hydrogen infrastructure. • Foster the development of relevant skills and knowledge. • Implement a participatory approach involving various stakeholders in the policy design process. • Engage in international cooperation to acquire technical assistance and expertise in shaping the policy framework.						
Relation with other policies	• Industry. • Energy. • Climate. • Foreign direct investment. • Science, technology and innovation. • Skills development.						
Issues addressed	• Setting priorities based on a well-defined strategy provides policy direction and market foresight, thereby reducing risks for potential investors and stakeholders.						

2 Regulatory definitions and standards

Objective	• Establish clear, long-term regulatory definitions for the production of green hydrogen and for 'green value' associated with products manufactured using green hydrogen in end-user industries.

<table>
<tr><td>Key actions</td><td colspan="7">

Adopt existing international standards for green hydrogen production, i.e. International Electrotechnical Commission Standards for Hydrogen Safety (IEC 62282-2-100), or those developed under ISO Technical Committee 197 on hydrogen technologies, etc.
Participate in the development of new standards for hydrogen regulation by involving multiple stakeholders.
Adopt a definition for hydrogen that is supported by the government (“renewable”, “green”, etc.), including quantitative and qualitative definitions.
Incorporate hydrogen in national regulations, alongside other energy carriers and sources.
</td></tr>
<tr><td rowspan="2">Policy tools/ instruments</td><td colspan="7">
Production

Introduce national hydrogen regulations, covering hydrogen’s role as an energy carrier.
Adopt additionality requirements (technological additionality) and other criteria to ensure that new renewable energy capacity is specifically designated for green hydrogen production.

<table>
<tr><td>Technological additionality</td><td>Establish requirements for a power plant to be considered in addition to the baseline (e.g. setting a commissioning date)</td></tr>
<tr><td>Temporal correlation</td><td>Establish a maximum permissible time interval between electricity generation and its consumption in the electrolyser</td></tr>
<tr><td>Geographical correlation</td><td>Control the location of the renewable energy plant and electrolyser</td></tr>
</table>

Develop unified sustainability standards for clean technology manufacturing, including those facilitating the traceability of products and components.
Implement local content requirements for the establishment of new electrolysis and renewable power plants.

Local demand creation

Adoption of a technical industrial standardization process for green goods produced with green hydrogen by end-user industries as strategies for low-carbon manufacturing and sustainable practice.
Adoption of specifications for components and protocols to use new technologies to ensure quality control and security.
Development of guidelines for green public procurement to promote local ‘green’ content of goods and components that are part of government expenditure lists.
</td></tr>
<tr><td colspan="7">
Transport & distribution

Adopt standards for green hydrogen transmission.
Adopt technical standards for the repurposing of gas networks for hydrogen use to ensure safe operations.
Define specific green procurement requirements for storage facilities.
</td></tr>
<tr><td rowspan="3">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td>Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td>✓</td><td></td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="7">Others: National and international quality infrastructure and standardization bodies.</td></tr>
<tr><td>Aspects to be considered</td><td colspan="7">
Assess different factors such as current regulations for the use of renewable energy sources, reduction of lifecycle emissions, etc., as well as compliance with environmental standards and other specifications and requirements.</td></tr>
<tr><td>Relation with other policies</td><td colspan="7">
Industry.
Trade.
Energy.
Climate.
Science, technology and innovation.</td></tr>
<tr><td>Issues addressed</td><td colspan="7">

The standardization of technical industrial processes increases operational safety and reduces technology risks, providing certainty and transparency to investors about the development of green hydrogen projects.
The establishment of standards for green products and technology components produced with green hydrogen provides information and tools for evaluation to qualify for green hydrogen certifications and potentially gain access to a broader international market.
</td></tr>
</table>

<table>
<tr><th colspan="8">3 Inclusive business environment</th></tr>
<tr><td>Objective</td><td colspan="7">• Create a stable and predictable business environment by streamlining regulatory systems and making them more transparent.
• Reduce the cost of doing business for investors and entrepreneurs to attract long-term investment and stimulate the development of large-scale projects.
• Foster collaboration between large corporations and local small and medium enterprises.</td></tr>
<tr><td>Key actions</td><td colspan="7">• Revise bureaucratic procedures to simplify processes for initiating, operating and expanding projects, and for closing and/or reorganizing them.
• Ensure that relevant authorities at both the local and national levels possess the capabilities required to manage administrative procedures aligned with policy definitions for prioritized projects.
• Establish mutually beneficial partnership models for large corporations and local small and medium enterprises such as dialogue platforms, joint ventures and initiatives, as well as technology transfer, incentivized by public support.</td></tr>
<tr><td>Policy tools/ instruments</td><td colspan="7">Promote the installation of electrolysers and the use of renewables:
• Strengthen leasing mechanisms to facilitate long-term land allocation, particularly for hosting the necessary renewable energy sources for electrolysis.
• Determine the rent charged for public land leases based on the gap between a projects’ levelized cost of energy/hydrogen compared to the regional or global market.
• Establish open and transparent auctions to establish long-term power purchase agreements (PPAs) as a framework to attract investments in new projects for renewable electricity generation.
• Adopt international cooperation mechanisms to improve engagement with key stakeholders, including hydrogen-importing countries, technology suppliers, international development banks and regional hydrogen associations.
Streamlining administrative procedures to facilitate business development:
• Reduce cost and lead times for business registration and licensing.
• Simplify tax codes to encourage investment and entrepreneurship.
• Strengthen property rights and contract enforcement.
• Facilitate patent protection to encourage innovation.
• Establish effective dispute resolution mechanisms.
• Introduce insolvency frameworks.
Accelerate permitting procedures for the development of greenfield projects:
• Establish a ‘one-stop-shop’ as a single point of contact (government agency or department) to facilitate access to a range of support measures with the aim of reducing the administrative burden associated with all matters related to permitting.
• Provide online systems with guidelines, templates and comprehensive information on the application procedure’s documentation requirements.
• Establish interagency coordination and accountability mechanisms to facilitate effective interaction and prevent duplication of efforts.
• Ensure alignment with international technical standards for project implementation (i.e. technical engineering requirements for large-scale investment projects).
• Prioritize the development of environmental and social impact assessments.</td></tr>
<tr><td rowspan="2">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td>Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Aspects to be considered</td><td colspan="7">• Review and adjust formal requirements, procedures and practices.
• Adopt best practices to create favourable investment conditions for the development of green hydrogen projects.
• Conduct environmental and social assessments related to the planning of green hydrogen infrastructure and their impact on local communities.</td></tr>
<tr><td>Relation with other policies</td><td colspan="7">• Industry.
• Energy.
• Fiscal policy.
• Finance / economic.
• Infrastructure development and other construction-related policies.
• Land distribution and management policies.</td></tr>
<tr><td>Issues addressed</td><td colspan="7">• Reduce excessive regulatory barriers that slow down project development and discourage potential investors and industrial stakeholders.</td></tr>
</table>

Support for early movers

Policies to support project take-off and implementation:
Facilitate access to funding and other economic mechanisms to support early mover investments

1 Access to funding

Objective

- Provide financial assistance to reduce operational and capital expenditures for sectors that already use hydrogen as a fuel, including sectors such as steel, glass and ceramics (brownfield green hydrogen industrial projects), as well as for the development of new industrial facilities (greenfield green hydrogen projects) to attract new downstream industries to the national economy.

Key actions

- Launch exclusive rounds of government funding to provide direct support for the implementation of green hydrogen projects.
- Establish credit-enhancing mechanisms to facilitate the entry of senior lending into project structures as well as to attract institutional investors.
- Direct public R&D funding to support hydrogen demonstration projects.
- Strengthen international collaboration (international climate financing).

Policy tools/ instruments

- **Fast-tracking access to government financial assistance:** support capital investment for the development of local industrial projects through:
    - Direct public funding.
    - Co-financing or conditional grants.
    - Government-backed loans (soft, concessional, convertible, contingent, subordinated).
- **Public funding based on competitive bidding:** initiate a call for project proposals to allocate public resources or government contracts. Competitive bidding can be used to award subsidies, grants, incentives or other forms of public financial support to the most viable projects in accordance with specific objectives or criteria.
- **Government investment through equity financing:** support early-stage, high-risk green hydrogen projects in exchange for a share of ownership in the project. Government investment can signal a commitment to project development and success (green bonds for environmentally sustainable projects).
- **Blended finance:** attract private financing for development projects that are perceived as being too risky for private investment alone.
    - Provide concessional public funds (grants or low-interest loans) combined with commercial funds.
- **Public-private partnerships (PPP):** promote investments in green hydrogen development projects, including the construction and operation of hydrogen pipelines or other transport infrastructure.

Actors/ bodies involved

Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
✓	✓					✓

Aspects to be considered

- Create green financing taxonomies in alignment with international standards, including specific conditions for green hydrogen investment projects.
- Government budget allocation (availability and direction of public funds).
- FDI instruments and regulations.

Relation with other policies

- Finance/ economic.
- Fiscal policy.
- Industry.
- Energy.
- Climate.
- Foreign direct investment.

Issues addressed

- Reduce the perceived high financial risk for investors by providing financial support for project development.
- Attract private investment to maximize the efficiency of public spending.

2 Fiscal incentives, subsidies and guarantees

Objective

- Provide financial support for capital or operational expenditure of green hydrogen project investments through fiscal incentives and compensation mechanisms.

<table>
<tr><td rowspan="2">Key actions</td><td colspan="8">• Carry out public budget and financial planning.
• Carry out economic and social impact assessments.
• Conduct feasibility analyses to assess the political implications for the implementation of policy measures, for instance when dealing with sensitive issues such as the reform or discontinuation of subsidies.
• All of the policy tools/instruments below can be proportional to commitments made in social contracts.</td></tr>
<tr></tr>
<tr><td rowspan="2">Policy tools/ instruments</td><td>Production</td><td colspan="3">• Introduce long-term tax breaks to attract foreign vendors to partner with local investors, thereby generating joint investments in capital-intensive components.
• Offer subsidies for local content (equipment, work and services) in the establishment of new electrolysis plants.
• Provide tax incentives for the deployment of renewables (corporate income tax, equipment import tax, VAT).
• Accelerated depreciation.</td><td>Local market creation</td><td colspan="3">• Implement tax credits, exemptions and rebates or deductions to reduce the tax burden of green hydrogen investments. They can be granted either for investment, to support capital costs, or for output, supporting operational costs.
• Provide subsidies as a temporary means to compensate higher operational costs, offering a premium price on green hydrogen to industries that are starting to use it as an input.
• Issue first-loss guarantees as a public guarantee to support eligible projects to reduce the risk exposure of senior project lenders. The guarantee is not used if the project succeeds.</td></tr>
<tr><td>Transport & infrastructure</td><td colspan="7">• Apply the regulated asset base model (RAB) to incentivize private sector investment in large infrastructure projects by offering regulated returns guarantees.
• Provide specific incentives for hydrogen storage construction which involves defining specific requirements for storage capacity, safety standards and environmental considerations for public storage procurement processes.</td></tr>
<tr><td rowspan="2">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td colspan="2">Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td></td><td>✓</td><td></td><td></td><td>✓</td><td colspan="2">✓</td></tr>
<tr><td>Aspects to be considered</td><td colspan="8">• Economic feasibility studies,
• Budget strategic planning.
• Political conditions.</td></tr>
<tr><td>Relation with other policies</td><td colspan="8">• Finance/economic.
• Fiscal policy.
• Foreign direct investment.
• Industry.
• Energy.
• Climate.</td></tr>
<tr><td>Issues addressed</td><td colspan="8">• Reduce financial risk for project development through targeted economic instruments.</td></tr>
</table>

Demand creation

Policies to support the development of market conditions:
Stimulate demand creation for green hydrogen-based industries and value chain development

1 Mechanisms to stimulate commercial intermediary and final demand

Objective	• Provide a kick-start to markets to stimulate activity throughout the value chain.
Policy tools/ instruments	• **Green public procurement**: contribute to driving demand and scaling up the value chain through public sector investment. ◦ Support manufacturers of certified green goods produced with green hydrogen. ◦ Support locally manufactured components and employment in the green hydrogen value chain. • **Financial incentives**: stimulate the purchase of green goods produced with green hydrogen by reducing manufacturers' operational expenditures. ◦ Tax rebates. ◦ Premium price. ◦ Subsidies. • **Quotas and targets**: provide additional support to establish a stable market: ◦ Introduce quotas for a minimum quantity of green hydrogen used in specific market segments. ◦ Promote legal or voluntary targets to meet CO2 intensity goals at the sectoral level (low-carbon practices). • **Guarantee schemes**: provide support to cover operating costs: ◦ Provide offtake guarantees: contractual agreements to purchase a predetermined quantity of green hydrogen at a specified price over a certain period of time (e.g. Carbon Contracts for Difference schemes). ◦ Offer price guarantees: commitments by a government or other entity to pay a fixed price for green hydrogen, regardless of market price. The purchase volume is subject to competition against other producers.

Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓			✓	✓	✓

Aspects to be considered	• Ensure green financing taxonomies are harmonized with international standards, including green hydrogen investment projects. • Conduct economic and social impact assessments. • Assess quotas and targets related to national strategy. • Align the price with market support mechanisms to stimulate market creation.
Relation with other policies	• Finance / economic • Fiscal policy • Industry • Trade • Energy • Climate • Foreign policy
Issues addressed	• Provide mechanisms to address market distortions and bridge the cost competitiveness gap.

2 Certifications

Objective	• Create incentives for industries to adopt green hydrogen and other clean technologies, as certified products may enjoy preferential treatment in procurement processes and tax deductions, as well as grow demand driven by consumer preferences and the willingness to pay a premium price for 'green goods'.

<table>
<tr><td>Key actions</td><td colspan="7">Adopt methodologies and standards for carbon content evaluation.
Develop a certification methodology and align national hydrogen production with international practices to facilitate international trading.
Ensure the presence of certification bodies.</td></tr>
<tr><td>Policy tools/ instruments</td><td>Production</td><td colspan="2">Certification of green hydrogen production.
Certification of electricity from renewable sources.</td><td>Local market creation</td><td colspan="3">Adoption of certifications for green goods produced with green hydrogen. The labelling of products validates sustainability credentials (low-carbon manufacturing, emissions performance).</td></tr>
<tr><td rowspan="3">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td>Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td>✓</td><td></td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="7">Others: National and international quality infrastructure and standardization bodies.</td></tr>
<tr><td>Aspects to be considered</td><td colspan="7">Assessment processes with rigorous and continuous measurements that are subject to compliance with established criteria and standards, in addition to third-party verification.</td></tr>
<tr><td>Relation with other policies</td><td colspan="7">Industry.
Trade.
Energy.
Climate.
Science, technology and innovation.</td></tr>
<tr><td>Issues addressed</td><td colspan="7">Increase visibility of green hydrogen producers, as well as intermediate and end industries;
Validate a premium price to support the uncompetitive price of green goods.</td></tr>
<tr><td colspan="8">3 Value chain integration</td></tr>
<tr><td>Objective</td><td colspan="7">Optimize project development around geographical locations to promote sector collaboration, create synergies and maximize resource utilization.
Stimulate economic linkages among green hydrogen end-uses in industry and relevant infrastructure and production capacities.</td></tr>
<tr><td>Key actions</td><td colspan="7">Identification of potential locations and relevant projects.
Screening of potential winning use cases.
Promote sector coupling – integration and coordination of different sectors (energy, manufacturing, transportation).
Establish public-private partnerships to attract sector collaboration initiatives.</td></tr>
<tr><td>Initiatives/ programmes</td><td colspan="7">Green hydrogen industrial clusters: promote interdependent green hydrogen projects, focusing on industrial use and green goods manufacturing.</td></tr>
<tr><td rowspan="2">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td>Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td>✓</td><td></td><td>✓</td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>Aspects to be considered</td><td colspan="7">Specialized expertise, services, resources, suppliers and skills.
Assessments for cooperation, including sharing information about the evolving market, economic, regulatory and environmental contexts.
Assessments for optimizing geographical location for cluster development, planning and zoning of industrial areas (connection to infrastructure and transport).
Incentives to support the creation of consortia between multiple companies along the green hydrogen value chain.
Prioritization of public spending.</td></tr>
</table>

Relation with other policies	• Industry. • Trade. • Transport and logistics-related policies. • Climate. • Energy. • Finance/economic. • Fiscal policy.
Issues addressed	• Multiple end-users sharing production, transport and storage capacity reduce the costs of infrastructure and can optimize the distribution of risks and investments. • Sharing of resources increases efficiency and reduces energy and material waste. • Collaboration strategies can help scale the market.

Collaboration initiatives

Policies to support collaboration and knowledge creation:
Knowledge sharing and collaboration mechanisms to foster innovation throughout the green hydrogen value chain

1 Targeted training and educational initiatives

Objective	• Provide targeted education and training programmes for professionals across different sectors to develop skills and knowledge to safely engage with hydrogen technologies. • Provide capacity development to policymakers at all levels about key areas of the hydrogen economy to support the formulation of policy frameworks and national strategies.
Key actions	• Raise awareness about hydrogen's potential in achieving low-carbon development objectives through broad educational campaigns centred around green hydrogen technologies. • Design targeted programmes to enhance the workforce's existing skill set and competencies through specialized professional training. • Safety training tailored to specific groups to ensure secure implementation, operation and maintenance of hydrogen and fuel cell equipment.
Initiatives/ programmes	• Technical and vocational training programmes. • Strategy development to include green hydrogen in the academic syllabus of higher education institutions, research programmes and workforce development programmes. • Conferences and forums related to hydrogen policy.

Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓	✓	✓	✓	✓	✓

Aspects to be considered	• Educational and training material. • Specialized expertise and resources. • Comprehensive courses and apprenticeships. • Business engagement.
Relation with other sector policies	• Education. • Science, technology and innovation. • Industry. • Energy. • Climate.
Issues addressed	• Knowledge gaps and skills shortages. • Safe engagement with hydrogen technologies.

2 Knowledge exchange

Objective	• Provide incentives for knowledge sharing among firms so new market entrants can benefit from practical experiences of previous projects in terms of R&D, technology transfer and public funding.
Key actions	• Coordination of efforts with local and international partners. • Promote knowledge sharing from demonstration projects that were supported by public funding. • Long-term stimulation of a country's own green hydrogen-related R&D.
Initiatives/ programmes	• Target funds to stimulate the sharing of knowledge and experience (for instance, directing funds towards consortia instead of individual firms to facilitate the diffusion of innovation and cost reductions along the value chain). • Promotion of resource-efficient technologies that minimize costs in production, offer potential alternatives and demonstrate the potential to address circular economy principles (re-use, repairability and recyclability). • Promoting dialogue and knowledge dissemination by sharing expertise in the deployment of projects with a better understanding of local contexts and specificities. • Collaborative research to enhance understanding and reduce uncertainties regarding risks associated with hydrogen leakage and its climate impact. • Forums (conferences and dialogues).

Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓		✓	✓	✓	
Aspects to be considered	• Technical knowledge and material availability. • Intergovernmental knowledge sharing on policy approaches. • Interconnected information platforms to support international partnerships for clean technology manufacturing.						
Relation with other policies	• Education. • Science, technology and innovation. • Industry. • Energy. • Climate.						
Issues addressed	• Support research and knowledge creation and diffusion to enhance understanding of hydrogen economy.						

3 Government informational digital platforms

Objective	• Facilitating the exploration of financing, economic and technical alternatives that impact project viability and funding options.						
Key actions	• Create public matchmaking platforms to connect funding options with stakeholders. • Establish information platforms to provide guidance and support to project promoters and/or provide direct assistance for project development.						
Initiatives/ programmes	• Digital platforms to provide targeted support.						
Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓			✓		✓
Aspects to be considered	• Industrial platforms. • Green hydrogen private associations platforms. • National information platforms directed at attracting foreign direct investment.						
Relation with other policies	• Industry. • Foreign direct investment policies.						
Issues addressed	• Provide information related to green hydrogen project development. • Reduce coordination barriers for allocation of finance options and resources.						

Just transition

Policies to ensure socio-economic benefits:
Inclusive sharing of the hydrogen value chains' benefits and safeguarding ecosystems along with energy, food and water security

1 Benefit-sharing mechanisms

Objective	Ensure a **fair distribution** of the benefits arising from the investments and profits associated with the green hydrogen value chain. Achieve **inclusive public participation** and involvement of local communities in strategy and project development to ensure public acceptance of green industrial development. Accept and navigate **trade-offs** between different dimensions of justice, equity and participation rather than focusing on a predetermined "win" in all dimensions.
Key actions	• **Reinforce** the reinvestment of corporate hydrogen profits in the host country. • **Support** citizen participation in the development of energy, hydrogen or industrial projects. • **Reinvest** public fiscal revenues in social causes. • **Use** fiscal revenues for direct payments to citizens. • **Save** fiscal revenues for future generations and/or long-term public investments.
Initiatives/ programmes	• Impose restrictions on excessive **corporate income repatriation** and promote benefit-sharing requirements. • Require **community development investments** for investment participation in hydrogen projects. • Establish **citizen participation schemes** for energy, hydrogen and industrial projects such as energy cooperatives and other forms of "distributed ownership". • Earmark fiscal revenues for broad-based or **pro-poor spending**, e.g. for education and research or structural transformation of regions, especially those negatively affected by the transition to a low-carbon economy. • Establish annual dividend schemes, resource-to-cash payment programmes or a national hydrogen fund.

Actors/ bodies involved	Government	Business/private sector associations	Civil society	Academia/esearch institutions	International organizations	Bilateral/multilateral cooperation	Development banks/ donor agencies
	✓	✓	✓	✓		✓	

Aspects to be considered	• Inclusive civil society participation. • Research to prioritize reinvestment cases. • Management of direct payment schemes or intergenerational funds.
Relation with other sector policies	• Industry. • Finance/economic. • Fiscal policy. • Foreign direct investment. • Social policy.
Issues addressed	• Public acceptance of industrial hydrogen projects. • Local socio-economic development.

2 Social contracts

Objective	• Protect and improve the welfare of local communities throughout the establishment of the green hydrogen value chain. • Safeguard and improve energy, water and food security of local communities.
Key actions	• Identify the vulnerabilities and needs of local communities. • Assess the expected impact of hydrogen projects on local communities, including negatives such as environmental degradation and opportunities such as employment and energy access. • Mitigate security risks to local communities and realize potentials for welfare improvement.

<table>
<tr><td>Initiatives/ programmes</td><td colspan="7">

Conduct socio-economic and environmental impact assessments.
Invest in community development, e.g. improved housing and healthcare facilities.
Train and employ local residents in the operation and maintenance of power plants, creating job opportunities and contributing to the local economy.
Require developers to allocate a share of renewable energy production to local electricity consumption, ensuring cleaner and more reliable power for all, e.g. through social licensing.
Reach agreements with developers to support local agriculture through sustainable water management practices or desalination projects sized to provide water to the local population, e.g. through social licensing.

</td></tr>
<tr><td rowspan="2">Actors/ bodies involved</td><td>Government</td><td>Business/private sector associations</td><td>Civil society</td><td>Academia/esearch institutions</td><td>International organizations</td><td>Bilateral/multilateral cooperation</td><td>Development banks/ donor agencies</td></tr>
<tr><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Aspects to be considered</td><td colspan="7">

Social and environmental impact assessments.
Educational and training material.
Comprehensive courses and apprenticeships.
Energy grid planning.
Land management strategies.
Agreements with project developers.

</td></tr>
<tr><td>Relation with other policies</td><td colspan="7">

Education.
Skills development.
Industry.
Energy.
Climate.
Environmental policy.
Social policy.
Land distribution and management policies.

</td></tr>
<tr><td>Issues addressed</td><td colspan="7">

Energy, water and food security.
Community welfare.
Unemployment.

</td></tr>
</table>

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United Nations Industrial Development Organisation (UNIDO)
Vienna International Centre
Wagramer Str. 5, P.O. Box 300,
A-1400 Vienna, Austria

+43 1 26026-0

www.unido.org/hydrogen

hydrogen@unido.org

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