International Renewable Energy Agency

Green hydrogen strategy

A guide to design

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The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Publications and editorial support were provided by Francis Field and Stephanie Clarke.
For further information or to provide feedback: publications@irena.org

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Contents

Figures

Tables

Boxes

Abbreviations

°C	degrees Celsius
AFID	Alliance for Industry Decarbonisation
BCA	border carbon adjustment
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
COP	United Nations Climate Change Conference
EG	empowered group
EU	European Union
EUR	euro
FCEV	fuel cell electric vehicle
GW	gigawatt
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
kWh	kilowatt hour
LCOH	levelised cost of hydrogen
LTES	long-term energy scenarios
Mt	megatonnes
MW	megawatt
MWh	megawatt hour
PEM	proton exchange membrane
R&D	research and development
RFNBO	renewable fuels of non-biological origin
SC	stakeholder consultation
SOEC	solid oxide electrolyser cell
TRL	technology readiness level
TW	terawatt
TWh	terawatt hour
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
USD	United States dollar

1. Why this report?
Introduction

Roughly 100 years ago, in February 1923, futurist John Haldane delivered a lecture at Cambridge University on wind farms that would provide England with clean and cheap electricity to produce hydrogen; he also envisioned the use of underground hydrogen storage to supply energy when the wind was not available (Haldane, 1923).

Since then, there have been several attempts (for example, during the oil crisis of the 1970s) to scale up hydrogen, particularly as a clean fuel to replace oil. Each occurrence of a "hydrogen wave of interest" marked a distinct phase in the exploration and development of hydrogen as a viable energy solution (see section 2).

The most recent phase is linked to international efforts to avert dangerous climate change. Countries around the world agreed in 2015 that rapid decarbonisation is needed and adopted the historic Paris Agreement. According to the Intergovernmental Panel on Climate Change (IPCC), human activities have unequivocally caused global warming, and in the last decade the average global surface temperature reached 1.1 degrees Celsius (°C) above pre-industrial levels. Based on the findings of Working Group III of the IPCC's Sixth Assessment Report, global temperature is likely to exceed 1.5°C of pre-industrial levels this century, based on current global targets expressed in National Determined Contributions (NDC), and even limiting warming to below 2°C would rely on a rapid acceleration of mitigation efforts after 2030.

The global consensus now is that hydrogen and its derivatives – produced in ways that yield low life-cycle greenhouse gas emissions (*i.e.* "clean hydrogen") – are part of the overall decarbonisation puzzle. They are a key solution to decarbonise hard-to-abate sectors, as well as for the large-scale, long-term storage and transport of clean energy. The role of clean hydrogen (see Box 2 for definitions) and its derivatives in industry to reach net-zero greenhouse gas emissions, and in mitigating emissions in the transport sector, were highlighted in the latest IPCC report on mitigation of climate change (IPCC, 2022).

At the 2023 United Nations Climate Change Conference (COP 28) in Dubai, United Arab Emirates, the Parties recognised for the first time the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5°C pathways, and were called to accelerate the adoption of "low-carbon hydrogen" (UNFCCC, 2023). To set this route, many countries are actively developing national hydrogen strategic documents, with the objective of setting targets, informing the population and creating investor confidence (Box 1).

Box 1 Creating investor confidence

Transitioning to a sustainable energy system poses a significant challenge for industries entrenched in conventional, carbon-intensive practices, particularly as they navigate towards cleaner, more sustainable alternatives such as green hydrogen.

This transition is also about ensuring that investments remain viable and productive in a low-carbon future. Green hydrogen, recognised for its potential to provide a "step change" in the energy landscape, has captured the interest of forward-thinking industrial players. These companies may aim to be "first-movers" in adopting green hydrogen, driven by an understanding of the need to reduce their carbon footprint and maintain competitiveness in a rapidly evolving market.

However, the enthusiasm for green hydrogen is tempered by challenges (see section 8). The cost of producing green hydrogen is much higher than conventional methods, and there is a pressing need to stimulate demand and to establish regulatory frameworks to support widespread adoption. A lack of clear direction from governments creates uncertainty, which can be detrimental to the competitiveness of local industries in international markets and can hinder their ability to secure financing and investments for green hydrogen projects.

A comprehensive green hydrogen strategy, developed and committed to by the government, can provide the much-needed pathway. A strategy would not only signal the government's commitment to a sustainable energy future, but also improve the business case for first-movers in the industry. The development of a green hydrogen strategy is crucial for attracting new investors, serving as a powerful commitment statement from the government and presenting a vision for the sector's future. This reduces investment uncertainties and strengthens the business case for sector growth. Strategies also inform local policy makers and regulators, aligning them with national investment objectives to help ensure that local policies and regulations support sector growth, minimising bureaucratic impediments.

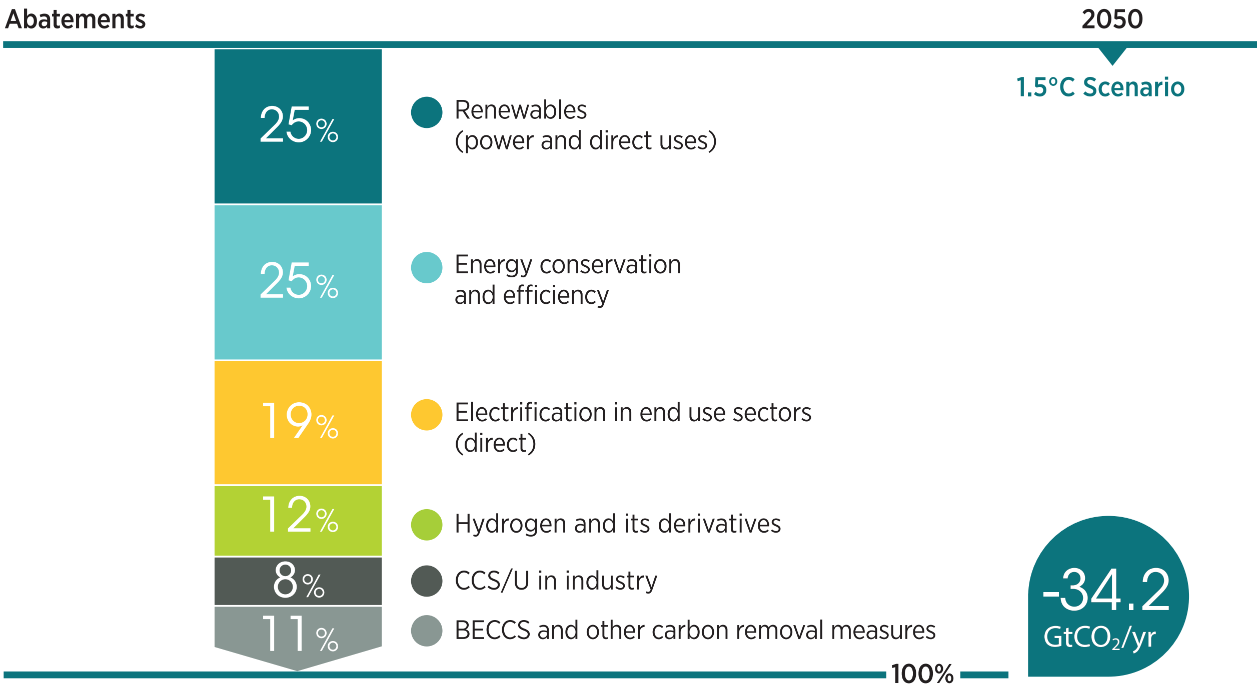
In developing countries, green hydrogen strategies act as tools for risk identification in emerging sectors, providing comprehensive risk assessments that highlight obstacles and actions needed to mitigate risks. This clarity and upfront acknowledgment of risks are pivotal for providing confidence to investors.

Ultimately, the success of green hydrogen in transforming the energy sector depends on collective efforts. Government strategies, industry innovation, and regulatory support must align to foster the sector's growth. Involvement of industry to inform the strategy making can support the identification of local priorities and barriers (see sections 5 and 8).

The 1.5°C Scenario developed by the International Renewable Energy Agency (IRENA), as set out in the Agency's *World Energy Transitions Outlook*, also highlights the important role of hydrogen. The scenario describes an energy transition pathway aligned with the ambition to limit the increase in the global average temperature by the end of this century to 1.5°C, relative to pre-industrial levels. It prioritises readily available technology solutions, which can be scaled up at the necessary pace to achieve the 1.5°C goal.

In the 1.5°C Scenario, clean hydrogen and its derivatives account for 12% of the overall reduction in carbon dioxide (CO_2) emissions by 2050 (Figure 1). Reaching this share will require enormous efforts, with clean hydrogen production increasing from 0.7 million tonnes in 2022 to 523 million tonnes annually by 2050. The share of green hydrogen in clean hydrogen is expected to be 94% in 2050. Investment needs for clean hydrogen infrastructure – including electrolysers, infrastructure, fuelling stations, bunkering facilities and long-term storage – will need to increase from USD 1.1 billion in 2022 to USD 170 billion annually by 2050. The cumulative installed capacity of electrolysers would increase from 550 megawatts (MW) in 2020 to 5.7 terawatts (TW) by 2050 (IRENA, 2023a).

Figure 1 CO_2 emissions abatement potential in IRENA's 1.5°C Scenario by 2050



Notes: BECCS = bioenergy with carbon capture and storage; CCS/U = carbon capture and storage/utilisation; $GtCO_2$/yr = gigatonnes of carbon dioxide per year.

Source: (IRENA, 2023a).

1.1 National hydrogen strategic documents

Hydrogen strategic documents serve as a comprehensive presentation of nationally defined targets related to scaling up a clean hydrogen sector domestically and abroad. They cover factors including (sectoral) demand, production, the country's economy, export capabilities, standards and certification, and challenges and opportunities. These topics are often explained in terms of policy ambitions and measures that are required to accelerate the adoption of a national clean hydrogen sector, including the scaling up of technologies.

In short, national hydrogen strategic documents aim to demonstrate the commitment of policy makers to harnessing the potential of clean hydrogen across different sectors (see also Table A.3). These documents can provide a clear vision and direction for policy makers, investors, and industry stakeholders, creating an environment conducive to innovation, investment and market development.

The development of national hydrogen strategic documents reflects the understanding that transitioning to a low-carbon economy requires not only ambitious emission reduction targets, but also a comprehensive and integrated approach to clean energy solutions that spans the whole economy.

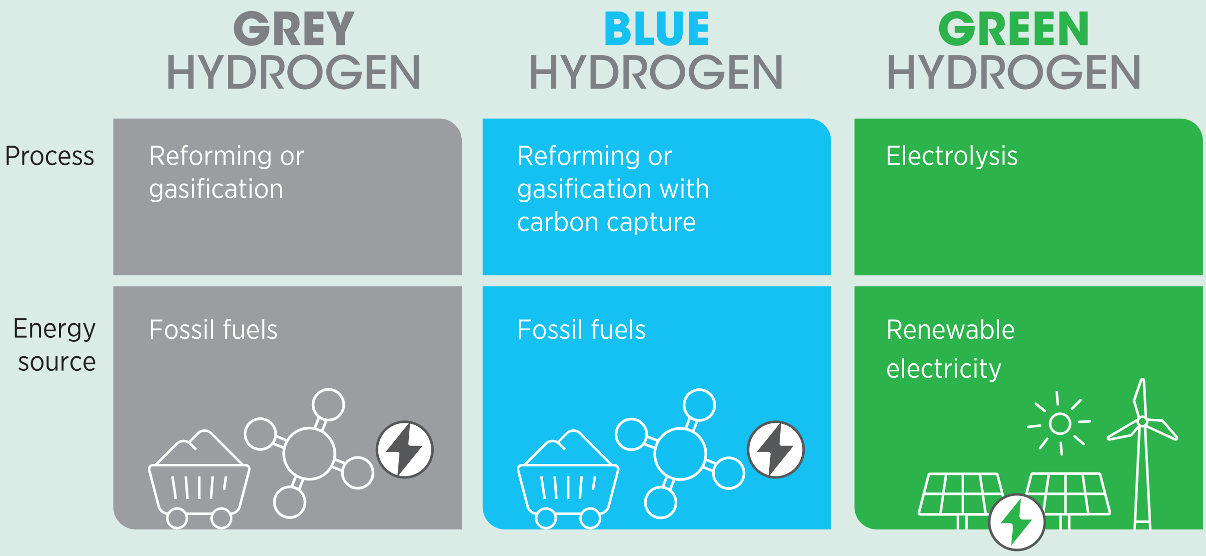
National hydrogen strategic documents differ substantially among countries, and often several documents are published within the same jurisdiction. As a result, these documents vary in content, size, style and depth of assessment. More recent strategic documents benefit from the experience of some previous ones.

There is no international standard for drafting hydrogen strategic documents. No generally accepted established practice exists yet, and countries individually approach the writing of these documents. Therefore, across countries, there exist divergences in approaches and definitions– for example, in the use of "colour-based" definitions for hydrogen and its derivatives (Boxes 2 and 3).

Box 2 Definitions of hydrogen

In public research and strategic documents, an approach to distinguishing the many types of hydrogen involves a conditional "colour-based" classification, valued for its simplicity. For instance, IRENA refers to green, blue and grey hydrogen (Figure 2). Clean hydrogen encompasses all the non-grey variants.

Figure 2 Selected shades of hydrogen



Source: (IRENA, 2020a).

Various jurisdictions and purposes dictate differing requirements to clarify what exactly is the hydrogen supported by policies, with regard to hydrogen-related life-cycle greenhouse gas emissions coverage, maximum allowable carbon footprint, preferred hydrogen production pathways, energy sources for such production, and so forth (IRENA, 2023b).

This study focuses on the topic of national hydrogen strategies, where the aforementioned differences in approaches to hydrogen definitions are fully reflected. For this reason, in the text other descriptors such as pink, renewable, electrolytic, low-carbon hydrogen and others are applied when used in policy documents.

The analysis, conclusions and recommendations presented in this report will be valuable to policy makers regardless of their approach to defining hydrogen.

Box 3 Definitions for this study

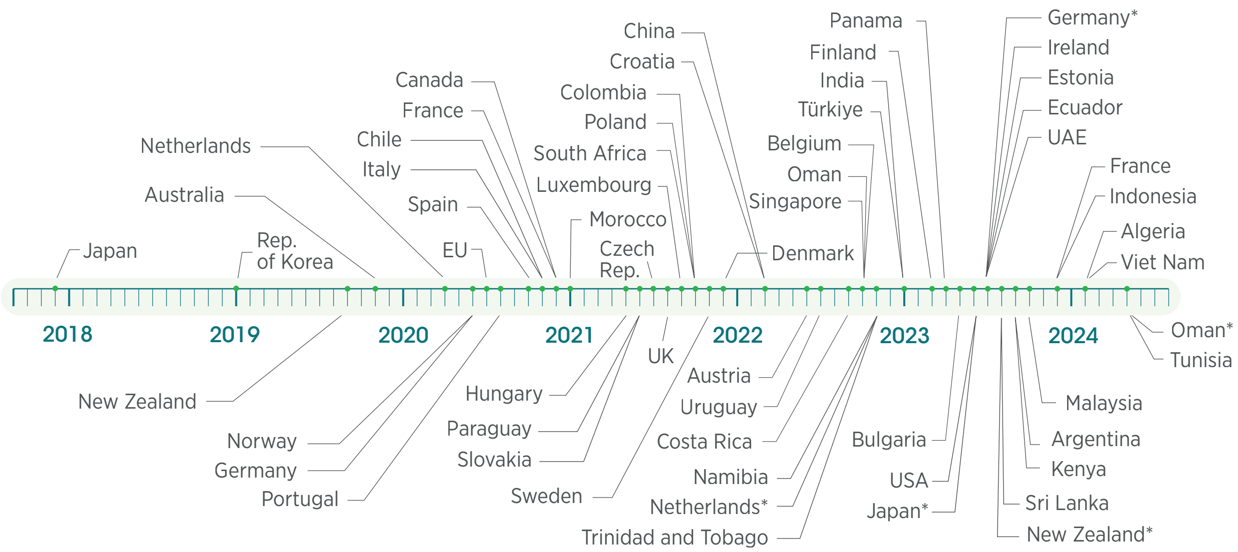
This study adopts the following approach to defining hydrogen strategic documents:

- A **national hydrogen strategy** is a long-term government document that outlines priorities, goals, barriers, opportunities and stages for developing a hydrogen sector within a country. It sets targets, addresses concrete policies and evaluates their coherence with existing energy policy.
- A **national hydrogen roadmap** outlines the approach to hydrogen deployment within a country, lacking clear goals but serving more as a framework for discussion. Unlike strategies, roadmaps usually are not formally adopted by the government but provide integrated plans, prioritising short-term actions, research areas and crucial demonstration projects. They are sometimes referred to as "vision documents", "white papers", "guidelines", etc.

1.2 More than 50 examples

As of May 2024, 46 national (and supra-national) strategies and 8 roadmaps on hydrogen had been drafted and published across the globe, and at least 20 more countries were in the process of making or publishing such documents (Figures 3 and 4). Thus, at least 74 countries are already involved in strategic planning of the clean hydrogen sector. A complete list of national hydrogen strategies and roadmaps as of May 2024,[1] with links, is provided in Table A.5.

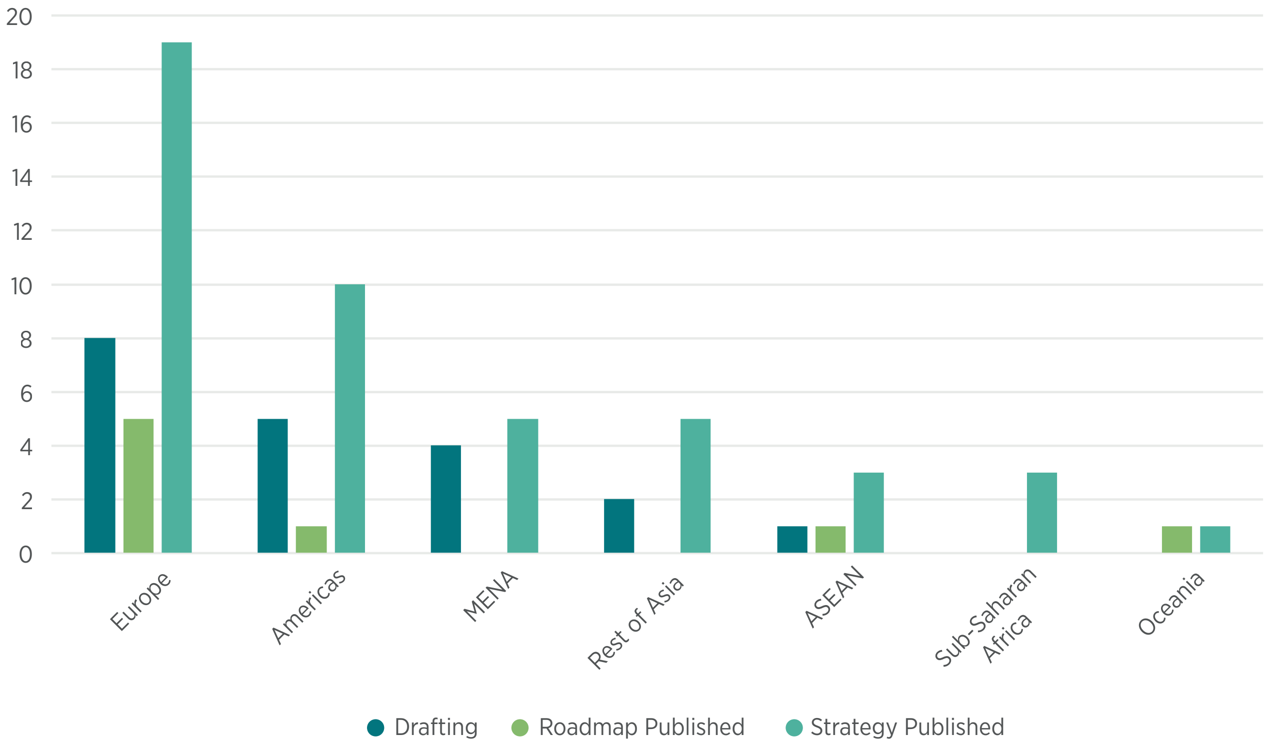
Figure 3 Timeline of hydrogen strategies and roadmaps (as of May 2024)

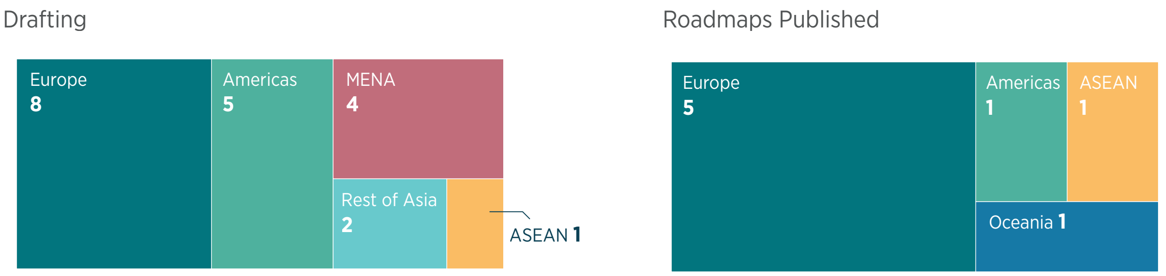


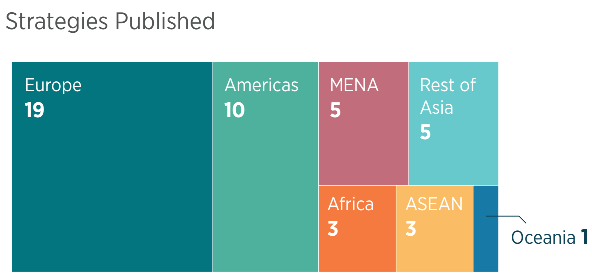
Note: Updates are indicated with an asterisk; EU = European Union; Rep. of Korea = Republic of Korea; Czech Rep. = Czech Republic; UAE = United Arab Emirates; USA = United States of America.

1 This latest data notwithstanding, the present study is based on strategies published as of March 2024.

Figure 4 Status of national hydrogen strategies and roadmaps (as of May 2024)







Notes: ASEAN = Association of Southeast Asian Nations; MENA = Middle East and North Africa.

Almost half of hydrogen national strategies have been published by European countries (including the EU strategy[2]). Countries in all seven macro-regions of the world are working on new strategic documents, with countries in Europe, the Americas, and the Middle East and North Africa region drafting nearly 80% of the total (Figure 4). However, the statistics are evolving rapidly as more countries develop hydrogen strategies or roadmaps (the writing of these documents itself usually takes a year or more).

Figure 5 Map of countries with national hydrogen strategies published (as of May 2024)

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Source: (IRENA, 2022d).

2 Hydrogen strategies usually have varying titles. For the sake of simplicity, in this report the strategies are referred to as "national strategy" (*e.g.* Singaporean strategy) and "national roadmap" (*e.g.* Italian roadmap).

1.3 Scope of the report

This report provides an analysis of hydrogen strategies and roadmaps developed by various countries in recent years. It aims to guide policy makers in crafting effective strategies that set clear targets, engage the public and build investor confidence (Box 1). The report's primary audience is policy makers drafting the first hydrogen strategy or roadmap, or policy makers updating a previous strategy in response to changed circumstances. However, the report is also relevant to think-tanks and other players that are ready to meaningfully contribute to the development of a country's hydrogen sector and that may desire to either understand or participate in the drafting exercise.

The report is structured around several key questions and aims to guide policy makers through the process of developing effective green hydrogen strategies. These questions are designed to prompt consideration of the motivations behind hydrogen strategy development.

Part 1 of the report is about the foundation of the work. The report begins by identifying the main policy drivers and examining past and current interest in green hydrogen as an energy solution (section 2). It then discusses the importance of stakeholder engagement (section 3), the integration of green hydrogen strategies within wider energy planning frameworks and the technical representation of hydrogen in long-term energy scenarios (section 4).

Part 2 moves to the topic of how to set the route. Here, the report assists in priority setting, identifying factors that can drive the decision-making process towards specific sub-sectors (section 5). It then examines the complexities of establishing a hydrogen trade – identifying roles that countries may play as exporters, importers, hubs or self-reliant entities (section 6) – followed by an assessment of potential target-setting options (section 7). Part 3 touches on the identification and overcoming of barriers to hydrogen sector development, including technological, regulatory, market-related and public perception challenges (section 8), and presents practical solutions to support hydrogen sector development and their integration in a hydrogen strategy (section 9). Finally, it outlines a step-by-step process for policy makers for drafting effective hydrogen strategies (section 10).

This report is part of IRENA's ongoing programme of work to provide its member countries and the broader community with expert analytical insights into the potential options, enabling conditions and policies that could deliver the deep decarbonisation of economies (Box 4).

Box 4 IRENA's work on green hydrogen and hard-to-abate sectors

IRENA's *World Energy Transitions Outlook* provides a detailed roadmap for emission reductions on a pathway consistent with a 1.5°C goal, alongside assessments of the socio-economic implications (IRENA, 2023a). Building on this, IRENA is analysing specific facets of that pathway, including the role of green hydrogen and its derivatives in the transition. This work encompasses the policy and financial frameworks needed, and opportunities for international collaboration to drive progress towards achieving shared goals. Recent IRENA publications on green hydrogen include:

- *International trade and green hydrogen: Supporting the global transition to a low-carbon economy* (IRENA and WTO, 2023).
- *Water for hydrogen production* (IRENA and Bluerisk, 2023).
- *Green hydrogen for sustainable industrial development: A policy toolkit for developing countries* (UNIDO, IRENA and IDOS, 2023).
- *International co-operation to accelerate green hydrogen deployment* (IRENA, 2024a).
- *Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7* (IRENA, 2024b).

These reports complement IRENA's work on renewables-based electrification, biofuels and synthetic fuels, and all the options for specific hard-to-abate sectors. This analytical work is supported by IRENA's initiatives to convene experts and stakeholders, including IRENA Innovation Weeks, IRENA Policy Days and Policy Talks.

The **Collaborative Framework for Green Hydrogen** leverages the Agency's work on green hydrogen, the wealth of knowledge and expertise that exists within IRENA's Membership, and the benefits that may be reaped through wider global co-operation with other entities. It serves as an effective vehicle for dialogue, co-operation and co-ordinated action to accelerate the development and deployment of green hydrogen and its derivatives for the global renewable energy transformation.

IRENA also convenes two stakeholder networks that facilitate international collaboration on decarbonisation, including on hydrogen topics:

- The **Coalition for Action** forms a key international network to discuss industry trends, determine actions, share knowledge, and exchange best practices, with the vision to drive the global energy transition in line with Sustainable Development Goal 7 on clean energy for all. The Coalition's mission is to convene a global dialogue among non-governmental and governmental stakeholders to develop actions to increase the share of renewables in the global energy mix. Among the Coalition's three working groups, there is a dedicated workstream on decarbonising end use sectors and the role of green hydrogen in better integrating renewable energy solutions. The Coalition has developed briefs on the practical insights, technical considerations and certification of green hydrogen.
- The **Alliance for Industry Decarbonisation** (AFID) aims to support efforts to decarbonise industrial value chains, advance industry adoption of renewables-based solutions and aid in the accomplishment of country-specific net-zero goals. The AFID is focused on six decarbonisation pillars and enablers, including green hydrogen. The AFID calls for a globally harmonised approach towards a methodology and definition for identifying green hydrogen. Moreover, the industry considers that harmonisation is needed on regulatory and subsidy regimes governing the whole value chain of green hydrogen for facilitating growth in this sector.

PART 1

Foundation

2. Why green hydrogen?
Drivers and motivation

The reasons for which clean hydrogen is being pursued at political level depend on the identification of policy drivers, meaning the factors that shape and influence the development and implementation of policies. The policy driver selected can influence how a challenge is interpreted, the solutions that are proposed and the political support for a particular end use.

Since the current wave of interest in clean hydrogen is not the first one, analysis of the policy drivers of the past can inform the reasons for increasing or declining interest, as well as help predict future dynamics.

2.1 Policy drivers for hydrogen strategy making

Policy drivers are the factors that shape and influence the development and implementation of policies. In the context of a clean hydrogen strategy, selecting drivers that motivate the development of a hydrogen sector in the country can lead to a better framing for the future of the sector.

This process, often implicit, establishes the trajectory of the hydrogen industry, envisioning the country's role within it. A well-crafted strategy ensures that long-term objectives are met. Thus, careful evaluation of relevant drivers is essential, considering the country's unique circumstances and government objectives. This ensures that selected drivers are tailored to the local context, driving growth and success in the hydrogen sector.

The most common drivers mentioned in national strategies are presented below. A combination of key drivers underscores the examined national strategies. These drivers include reaching decarbonisation goals, accelerating innovative industrial development, diversifying energy exports, increasing energy security, supporting long-term renewable energy storage, improving air quality in cities, ensuring alignment with other strategic energy initiatives, responding to international market dynamics and, as illustrated by the Kenyan example , enhancing food security. Each of these drivers reflects the multi-faceted role that hydrogen is expected to play in addressing some of the most pressing global challenges, from climate change to economic development and beyond.

Reaching decarbonisation goals

The pressing need to take immediate and effective action to combat the global climate crisis and restrain rising temperatures is becoming increasingly evident. As a result, policy makers must escalate their endeavours to reduce or entirely eliminate emissions from all economic activities. Solutions that offer only partial reductions in emissions are insufficient. For instance, according to IRENA's *World Energy Transitions Outlook*, in the 1.5°C Scenario direct electrification is projected to achieve a 51% share in total final energy consumption. However, the remaining energy needs must be met by other means. These include biomass, clean hydrogen (and its derivatives), and hydrocarbons with 100% carbon capture and storage (IRENA, 2023a)

Completely decarbonising specific sectors, such as industry and transport, presents substantial technical and socio-economic hurdles, and so far limited solutions are available for these "hard-to-abate" sectors. Nevertheless, there exists a shared remedy for some of these formidable sectors: green hydrogen and its derivatives, which can function as a fundamental component in the production of chemicals and fuels or can be directly used as a clean energy source. Nearly all hydrogen strategies share a common goal: to substantiate their role in achieving decarbonisation objectives.

As of May 2024, among the 54 countries that had published national hydrogen strategies and roadmaps, around 90% had committed to achieving net-zero greenhouse gas emissions or climate neutrality, typically by the year 2050. Although net-zero commitments from countries often lack clarity and firmness, it is evident that without such commitments, there is considerably less incentive for a country to develop a national hydrogen strategy.

Accelerating innovative industrial development and competitiveness

The development of hydrogen technologies, including both production and end use applications, is currently at the early stages of growth. As the global hydrogen market continues to evolve, a massive scaling-up of these technologies (by three to four orders of magnitude) will be required. This presents a significant opportunity for economic growth through building local "industrial ecosystems" and is a driving factor in the deployment of the hydrogen sector.

This driver can be further split into three categories: hard-to-abate industries, local manufacturing and green industrialisation.

Hard-to-abate industries

The deployment of hydrogen technologies can enable hard-to-abate industries to transition from high-carbon to low-carbon processes, helping to reduce emissions and contributing to decarbonisation goals. Stakeholders in steelmaking and chemical production view green hydrogen as a solution to maintain their competitive edge in the energy transition and to gain advantages in markets where the carbon footprint of steel and chemicals carries a price.

Local manufacturing

Another driver is the creation of an innovative and competitive upstream technology industry, which includes the manufacturing of compressors, membranes, heat exchangers, bipolar plates and control unit solutions. The growth of the green hydrogen sector will require a significant increase in the production of these components, presenting opportunities for technology and manufacturing businesses to participate in this growing market.

Green industrialisation

Finally, the large potential for affordable green hydrogen (especially in the Global South) has the potential to attract new, green industries (UNIDO, IRENA and IDOS, 2023). This is reflected in the strategies of Global South countries that are willing to use this potential to kick-start industrialisation programmes. The drive for green industrialisation in the Global South aligns with development strategies, offering countries an opportunity to leverage their renewable resources, abundant land, and transport accessibility to establish industrial clusters focused on delivering green products using green hydrogen.

Energy export diversification

For energy exporting countries, tackling climate change and reaching net-zero emissions is often interlinked with the ambition of economic diversification. Conversely, most of these countries are planning to increase fossil fuel production, at least by 2030 (IRENA, 2019; UNEP, 2023). However, the carbon neutrality goals of key energy-importing countries – leading to a reduction in fossil fuel demand – pose long-term risks for energy exporters and threaten their economic well-being and geopolitical power. This challenge does not depend on an exporting country's decarbonisation strategy; it is an external challenge. For policy makers, diversifying the export mix by replacing fossil fuels with clean hydrogen is seen as a pathway to respond to this external challenge.

In addition, countries with good variable renewable energy resources (VRE) may seek to become exporters of green hydrogen, even if they are not traditional energy exporters. As the demand for green hydrogen and its derivatives increases, these countries aim to capture a share of the hydrogen export market and to reap the economic benefits that may come with it.

Increasing energy security

Around 80% of the global population lives in countries that are net importers of fossil energy (IRENA, 2022b). Energy security, or uninterrupted energy supply at affordable prices, has been a critical strategic issue for all energy-importing countries or regions.

Energy security as a driver for developing the green hydrogen sector takes two forms.

1. Self-production of green hydrogen as a feedstock for local industry. This would decouple local industries from having to import fossil fuels to produce grey hydrogen, avoiding the price fluctuations of goods tied with fossil fuel prices. As an example, natural gas makes up around 60-80% of fertiliser production costs in Europe (European Commission, 2019).
2. Diversification of suppliers. Green hydrogen can be produced at scale virtually anywhere in the world. This means that green hydrogen trade flows are unlikely to be cartelised. Therefore, green energy trade flows are unlikely to lend themselves as easily to geopolitical influence as oil and gas. At the same time, the main consumers of green hydrogen, at least in the early stages, are expected to be a few countries in the Global North, notably in the G7 (IRENA, 2022c, 2022d).

A situation of few buyers and many potential sellers reverses the dynamics of energy markets, creating an oligopsony, a market driven by only a few eminent buyers, who can pick the "winners" for economic and geopolitical reasons (Pepe, Ansari and Gehrung, 2023).

Supporting long-duration, large-scale renewable energy storage

As the power sector decarbonises, the share of VRE will have to grow to levels where over-generation becomes structural, and curtailment risk will increase substantially. There may be seasons when VRE generation exceeds demand even with the assistance of short-term storage solutions (*e.g.* pumped storage hydropower or lithium-ion batteries) and demand-side management. Seasonal storage will also require other solutions capable of storing energy on the scale of several terawatt hours (TWh).

For example, against the EU's annual natural gas demand of 360-400 billion cubic metres in 2022-2023 (IEA, 2023), the capacity of natural gas storage in underground gas storage as of November 2023 amounted to around 100 billion cubic metres, or about 25-27% of annual consumption (European Commission, 2024a). Similar scales of storage are observed in the oil and coal sectors.

Underground hydrogen storage is foreseen to provide an opportunity for long-duration, large-scale energy storage (IRENA, 2021a, 2022e). This allows green hydrogen to be produced and stored underground and then used seasonally, for example during periods when renewable power production cannot cover the demand.

Improving air quality in cities

Road transport is a significant source of emissions that degrade urban air quality and directly harms human health, including emissions of particulate matter, nitrogen and sulphur oxides, and benzo(a)pyrene. Since hydrogen fuel cell electric vehicles (FCEVs) do not emit harmful air pollutants, their deployment alongside the gradual decommissioning of petrol and diesel buses and trucks leads to air quality improvement in cities. For many hydrogen projects in China, the use of hydrogen in mobility is viewed as a strategy to reduce reliance on imported oil and to address air pollution, although there is less emphasis on the specific sources of hydrogen (Miller-Wang, 2023). However, the influence of this factor gradually diminishes as battery electric vehicles become more competitive, shifting the focus of FCEVs to heavy-duty long-haul transport (such as trucks and buses). This was a main driver for the hydrogen wave of interest in the early 2000s.

Band-wagoning

As the avalanche of hydrogen strategies appears, policy makers may feel the need to prepare a strategy to avoid missing the "hydrogen train". As neighbouring countries draft strategies, perhaps promising to export large amounts of hydrogen to key import markets (see section 6), policy makers may feel the need to set up a similar strategy to kick-start a similar market. Local stakeholders and the general public may push for specific solutions (*e.g.* FCEVs) that are high on their agendas. This is related to the "hype" and "fear of missing out" phenomena presented in section 8.

However, this rush to draft a strategy, while being highly politically desirable, may miss the opportunity to identify the solutions and the roles of the country in the hydrogen sector that have higher practical feasibility. This combination – high political desirability and low practical feasibility for a solution undertaken based on drawing lessons from other jurisdictions – has been defined as a "siren call" that has high potential for policy failure (Rose, 1991).

A new driver: Food security, the Kenyan example

In Kenya, a confluence of challenges has greatly impacted maize production and food security. The issues began in 2020 when a global surge in fertiliser costs occurred due to fertiliser supply shocks, exacerbated by factors such as disruptions related to the COVID-19 pandemic, rising input prices and export restrictions. This led to a staggering 50-60% increase in fertiliser prices in Kenya during 2020-2021, resulting in a drastic decline in maize production of 550 000 tonnes. This decline was attributed to the increased cost of fertilisers and persistently low rainfall, marking the most severe drought in four decades. Consequently, maize flour prices in the country surged 30-65% in 2022.

The situation worsened due to the conflict in Ukraine and soaring energy prices, which further propelled fertiliser costs in Kenya, leading to a 70% increase in 2022. Experts estimated that this fertiliser price hike could cause a 12% drop in maize yields in 2022, equivalent to around 400 000 tonnes less maize production. When combined with the 2020-2021 decline, this translates to nearly 1 million tonnes (Mt) less maize production over two years. As a result, around 3 million additional Kenyans (a 30% increase from earlier assessments in February 2022) now face acute food insecurity, particularly in the vulnerable arid and semi-arid lands regions (WFP and BCG, 2022).

The 2023 "Green Hydrogen Strategy and Roadmap for Kenya" aims to leverage green hydrogen as a solution to several critical challenges, with food security being a driver due to the potential impact that local green hydrogen production can have on reducing food price hikes. This strategy recognises the pivotal role of the agricultural sector in Kenya's economy and the vulnerability created by imported fertilisers. The strategy suggests that, by producing green hydrogen locally for fertiliser production, Kenya can improve food security and enhance resilience in the agricultural sector. The strategy emphasises that transitioning to green hydrogen can reduce the need for fertiliser imports, leading to cost savings and improved trade balances. Additionally, establishing a domestic market for green hydrogen derivatives would boost Kenya's export potential, leveraging its strategic regional position and enhancing its balance of payments.

Green hydrogen is also seen as a catalyst for green industrialisation in Kenya, as it enables the establishment of manufacturing value chains. This, in turn, can foster the development of various downstream industries and creates employment opportunities. Additionally, the green hydrogen industry can act as an anchor off-taker, providing the demand reliability necessary to drive the expansion of the power grid, accelerate the growth of the renewable energy sector and ultimately improve access to electricity services for the people of Kenya.

2.2 Past and current drivers: Hydrogen hype and hope

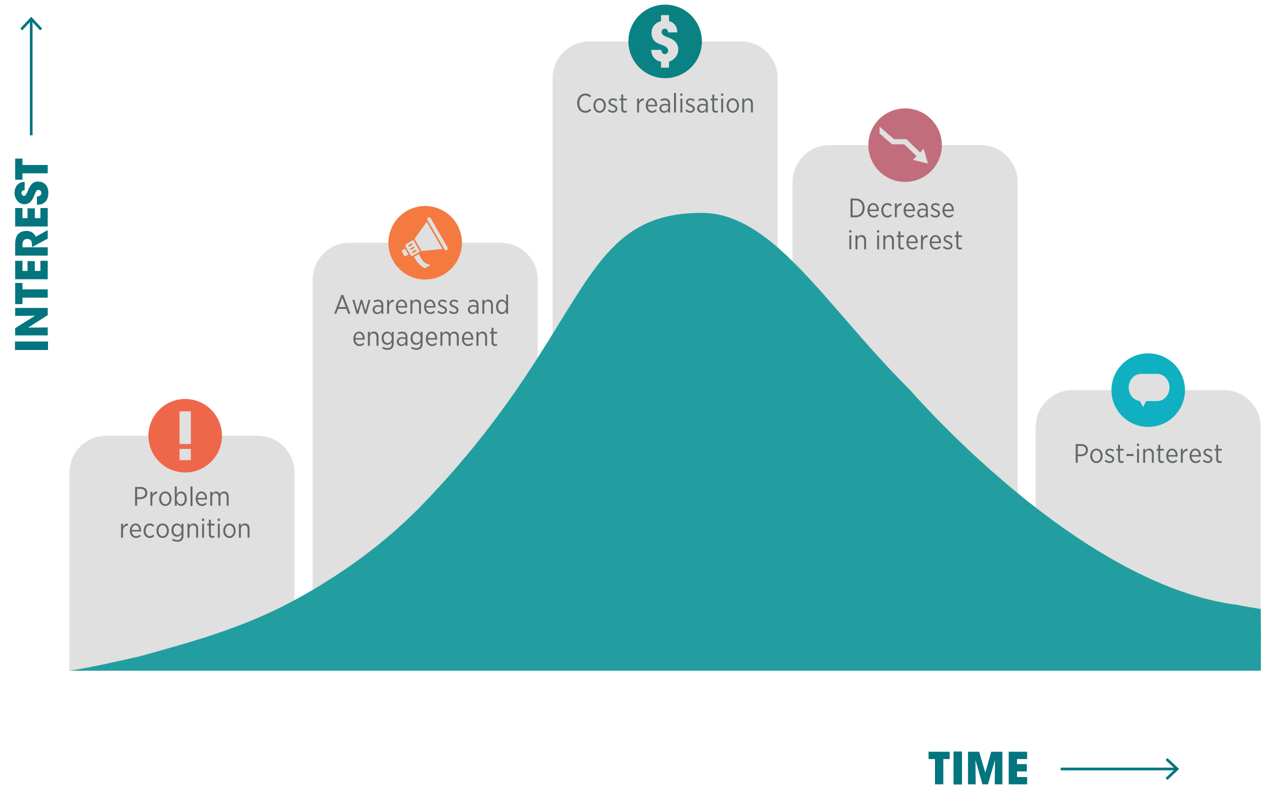
Hydrogen has received considerable attention as a potential solution for various challenges facing energy systems in the past. However, interest in this solution has always waned, possibly leaving the impression that hydrogen will remain a hyped solution with limited potential for large-scale adoption, since memories of past expectations may be rationalised according to the way things eventually turned out. This may also be related to a general lack of knowledge about the actual size of the current production and consumption of grey hydrogen and its greenhouse gas emissions.

To understand why past hydrogen waves of interest waned, and if the current one is meant to stay, it can be useful to analyse the drivers pushing such waves. Political scientists have already addressed and analysed waves of attention for various technologies, generalising the common trends and identifying the cyclical nature of agenda setting for policy makers and industrial players (Borup *et al.,* 2006; Downs, 1972; Newig, 2004; O'Leary, 2008; Ruef and Markard, 2010).

Broadly speaking, waves of interest can be seen as dynamics of sectoral or general attention towards a problem and its potential solution(s), which may rise and fall more-or-less independently of the factual development of the perceived problem or whether it is "solved" or not. These waves can be visualised in the following way (Figure 6):

1. **Problem recognition:** At the outset, a problem is recognised, but primarily by a limited group of experts, not reaching the broader public.
2. **Public awareness and engagement:** Specific policy drivers thrust the issue into the spotlight. This prompts both the general public and influential stakeholders to take notice, and potential solutions gain considerable attention.
3. **Cost realisation:** Over time, the social and economic costs associated with proposed measures begin to emerge more clearly.
4. **Decrease in interest:** Policy makers and the general public grasp the complexity and financial implications of solving the problem. This realisation can lead to public disheartenment and a shift in priority towards other issues.
5. **Post-interest:** In the final stage, the issue no longer commands the central attention of the public. Nevertheless, it remains poised for re-activation should new dimensions of the problem surface. In addition, institutions, research activities and political bodies may have been created to study and track the solution's technological advancement.

Figure 6 Dynamics of waves of interest



Based on: (Borup *et al.*, 2006; Downs, 1972; Newig, 2004; O'Leary, 2008; Ruef and Markard, 2010).

The policy drivers pushing a wave of interest can be seen as the expectations around the effects of the technological solutions, or, in other words, the hope to solve a current issue with a future application of a technology. Initial promises are set to attract attention from financial or political sponsors and to stimulate agenda-setting processes (both technical and political). The cost realisation phase and the subsequent decrease in interest depend on the incapacity for such promises to be deployed at the scale needed to resolve the issue. Finally, it has been noted that after the decrease in interest, a persistent post-interest phase subsists, where new knowledge, research and development (R&D) funds and public bodies are maintained to adopt the solution when technology permits it.

Hydrogen has experienced multiple waves of interest in recent history. However, none have led to sustained and significant investments on a scale sufficient to catalyse shifts in hydrogen's role to a potential global energy carrier. On the other hand, government investments, including in R&D, have allowed for the gradual advancement of hydrogen technologies over decades (as with fuel cells).

In the 1970s, the policy driver for hydrogen was the oil price shocks of 1972 and 1979. Hydrogen research started to gain recognition in the context of energy after the term "hydrogen sector" was coined by John Bockris in 1972 (Yap and McLellan, 2023). The initial concept of a hydrogen sector emerged during a period when there was growing awareness about fossil fuel depletion, energy security and the escalating air pollution associated with fossil fuels. Projections indicated that hydrogen, generated from sources such as coal or nuclear power, could play a crucial role in future energy provision, especially for transport. Similar concerns pushed for a large use of renewable energy and electrification.

However, in that decade, a clean energy sector was not a concern: in fact, interest waned as oil and gas resources remained abundant and oil prices stabilised. In this first wave of hydrogen, the post-interest phase saw the launch of the *International Journal of Hydrogen Energy* in 1976 and the establishment of the International Energy Agency's (IEA) Hydrogen and Fuel Cell Technology Collaboration Programme in 1977 (IEA, 2021; Yap and McLellan, 2023).

The 1980-1989 period represented a stagnant phase for clean hydrogen development. The second wave of interest was recorded in the 1990s. Emphasis was again placed on hydrogen for transport applications, in particular FCEVs. Major automakers introduced prototypes of FCEVs in the 1990s, but their progress was hindered by low oil prices in the latter half of the decade. During the early 1990s, scientists successfully decreased the platinum content in fuel cells to one-tenth of its initial quantity, leading to a notable reduction in manufacturing costs. Despite this significant improvement, investments in mass production of FCEVs were far too expensive for automakers and not a viable proposition, especially considering the lack of hydrogen refuelling infrastructure. Following this second wave of hydrogen interest, the post-interest phase saw different countries and regions (including Canada, the EU and Japan) allocated substantial funding for R&D on hydrogen solutions (Yap and McLellan, 2023).

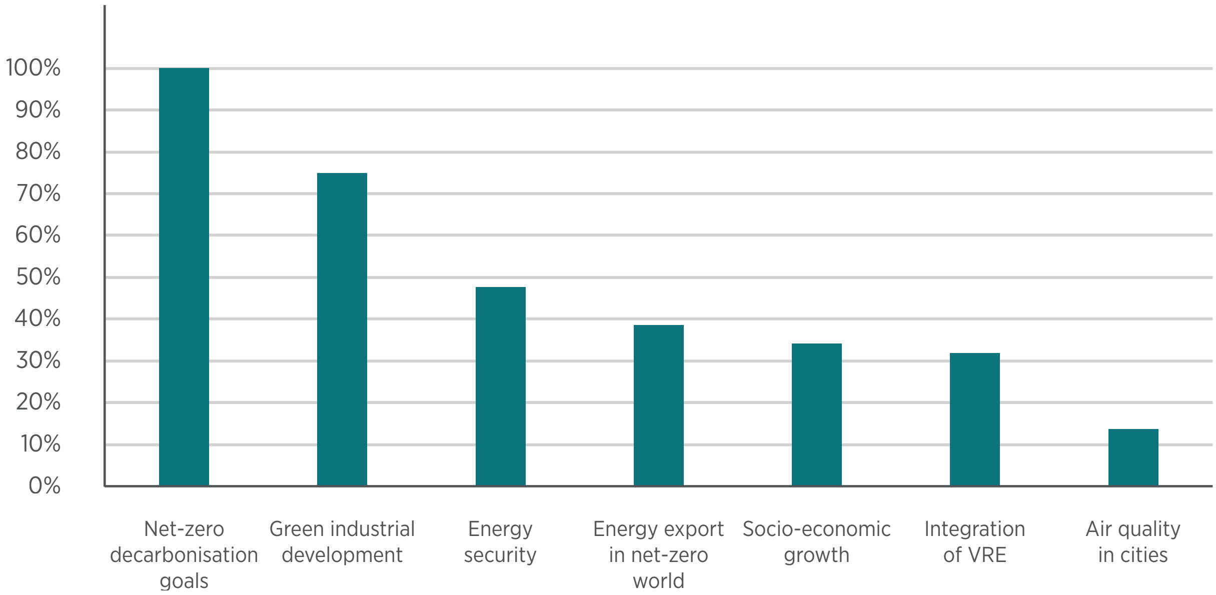
The third wave of interest was in the early 2000s, with a new focus on climate change (especially in Europe) and concerns about peak oil and diversification of energy supply. As a means of diversifying the energy mix, in 2003 the United States and the European Union launched a collaborative effort to accelerate the development of the hydrogen sector (White House, 2003). Chinese hydrogen policies, dating back to the 10th Five-Year Plan (2001-2005), initially targeted the transport sector to reduce oil import dependence and curb urban air pollution, with an emphasis on FCEVs (Miller-Wang, 2023).

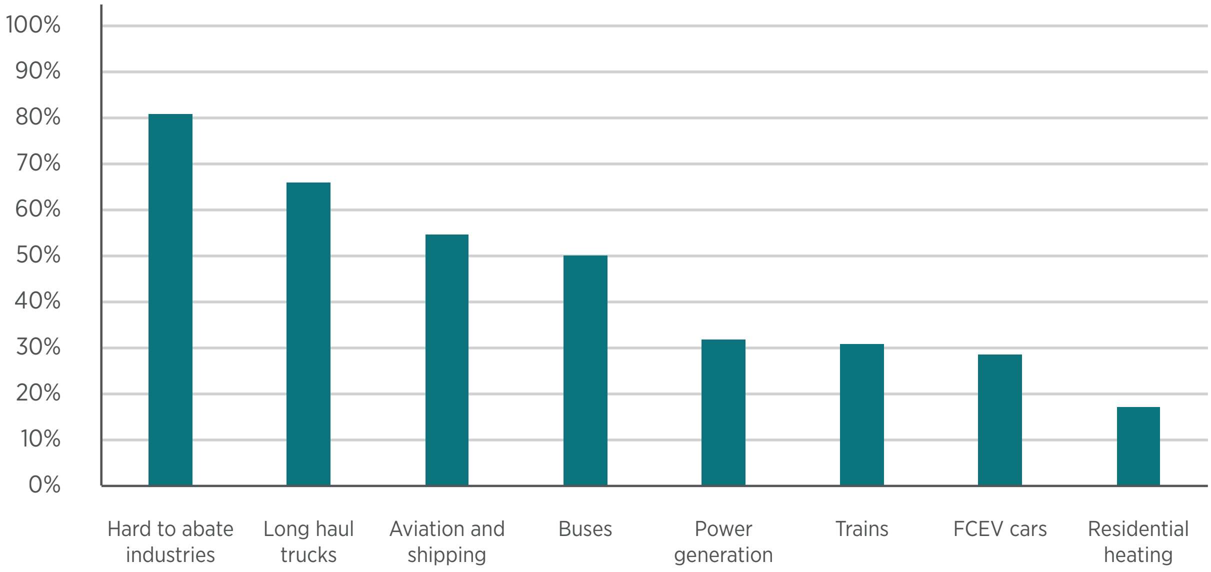
Again, the interest was focused on the automotive industry, with less prominent attempts to develop fuel cell applications for stationary use (not necessarily hydrogen-based). Hopes were also pinned on cheaper nuclear plants and the thermal splitting of water for hydrogen production. Still, governments and companies had only vague plans for hydrogen development (Solomon and Banerjee, 2006), and by 2010 interest in hydrogen waned due to the decline of the peak oil narrative, uncertainty about climate policies, and advancements in battery electric vehicles with lower infrastructure costs. In the post-interest phase, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) was established, and many hydrogen R&D programmes were funded (IEA, 2021; Yap and McLellan, 2023).

The various waves of interest were characterised by air pollution and energy security as main policy drivers, always with a specific focus on the transport sector, the main consumer of oil globally. Moreover, hydrogen waves of interest were localised in a few countries (typically in the Global North) that could afford new R&D efforts for blue or green hydrogen and that established activities on hydrogen that persisted in the post-problem phases. Emerging institutional structures (*e.g.* the establishment of hydrogen expertise within energy ministries, or hydrogen programmes) led to stabilising innovation activities, which maintained political support (Ruef and Markard, 2010).

The current wave of interest can be traced back to 2017, following the entry into force of the Paris Agreement in November 2016, the launch of the Hydrogen Council in January 2017, and the adoption of Japan's Basic Hydrogen Strategy in December 2017. Assessment of recent hydrogen strategies, a novelty compared to the past waves of interest, points to the main drivers. As shown in Figure 7, the current wave of interest is characterised by a strong interest in clean hydrogen as a decarbonisation solution and an industrial development opportunity. Hard-to-abate sectors are highly prioritised, compared to the light-duty transport sectors.

Figure 7 Drivers and sectors mentioned in national hydrogen strategies





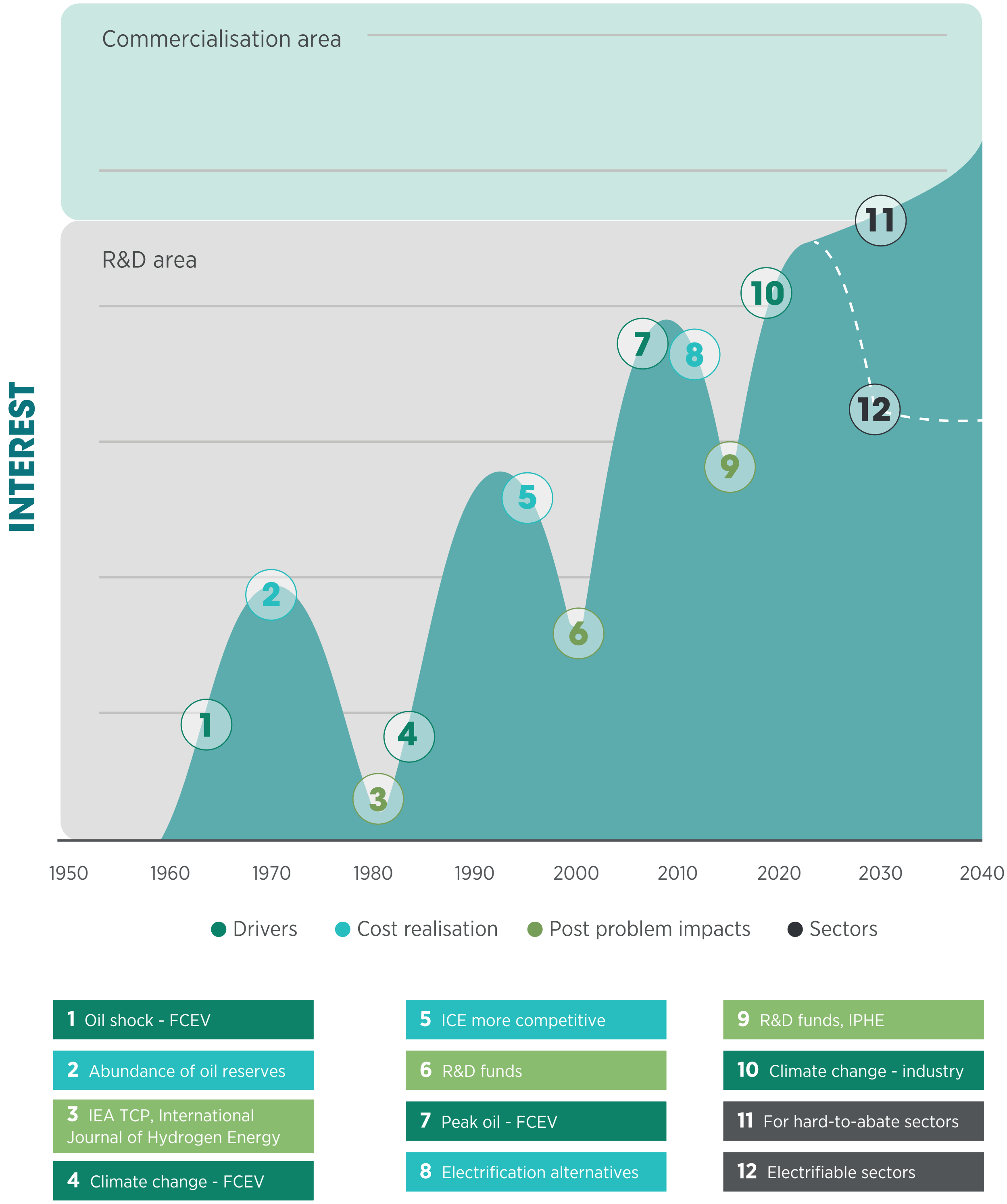
Notes: VRE = Variable Renewable Energy; FCEV = fuel cell electric vehicles. A scoring system was developed to objectively assess documents, categorising priorities in end use sectors and drivers as high (2), low (1) or none (0). See annex Figures A.3 and A.4. Each strategy underwent analysis, with scores assigned based on the relevance of elements. The aggregated scores for each element were then averaged across the number of evaluated strategies to quantify their priority level within the overall strategy framework.

The contrast with previous waves is notable. The cost realisation phase, with the gradual decrease of interest, is far from being achieved, suggesting that the business case for clean hydrogen may be stronger than in the past. In particular, countries are committing to sectors that cannot otherwise be decarbonised under the umbrella of net zero pledges; this makes potential counter-drivers unlikely to materialise unless climate change commitments are withdrawn.

The development of the clean hydrogen sector has been influenced by a variety of policy drivers. Despite past disappointments, previous waves of interest are integral to the historical context, as they allowed an acceleration of technological advancements that are still occurring.

The current wave of interest in the hydrogen sector might be different from past cycles, considering global efforts to reduce greenhouse gas emissions and to focus on hard-to-abate sectors. However, a partial decrease of interest could be foreseen for specific end use sectors. The use of hydrogen for light-duty vehicles, railways, and heating, for example, while supported at the beginning of the fourth wave, is facing realisation issues related to the easier feasibility of alternatives (electrification) and the cost of distributing hydrogen in these early stages (Figure 8). Correlated hopes, such as those for FCEVs or hydrogen heating, may fall in the already experienced decrease-in-interest phase, but solid expectations, based on reasoned priority setting (see section 5), are likely to face significant opposition unless climate policies are not repealed.

Figure 8 Historical waves of interest (illustrative)



Notes: FCEV = fuel cell electric vehicles; ICE = internal combustion engine; IEA = International Energy Agency; IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy; TCP = Technology Collaboration Programme.

3. **Who?** Stakeholder engagement

3.1 Introduction

Stakeholder engagement is essential in policy making, as it provides insight into the various agendas and priorities of all actors. This can help policy makers design measures that balance the needs of different stakeholders while still achieving overall policy goals.

Stakeholder engagement can help minimise unintended consequences by anticipating potential challenges arising from different agendas and values and pro-actively addressing them. Inclusive stakeholder consultation can serve for defining the scope of scenarios, ensuring proper communication of results, building trust, increasing acceptance of results and generally building common ground among stakeholders for future applications of the scenario or strategy (IRENA, 2023c; Kingdon, 1995; OECD, 2021).

Engaging with stakeholders can help build support for policies, which is critical for successful policy implementation and long-term sustainability. Policies that are supported by stakeholders are more likely to be implemented effectively and have a lasting impact (OECD, 2021). Moreover, the involvement of stakeholders ensures continuity in long-term planning beyond possible changes in political administrations. Therefore, engaging with stakeholders throughout the policy making process is crucial to ensuring that policies are effective, sustainable and equitable. Stakeholder engagement is understood (and pursued) to produce benefits well beyond bureaucratic accountability – increasing legitimacy, social justice and decision effectiveness. However, the effectiveness of such processes is not always guaranteed (IRENA, 2021b, 2022f, 2023c).

The inability of stakeholders to influence the policy process may *de facto* limit participatory approaches to governance, which may end up favouring industrial associations and other lobbies over public interest stakeholders (Crow, Albright and Koebele, 2017; Fung, 2006; Irvin and Stanbury, 2004; Yackee, 2012). This increases the risk of replicating prevalent power structures and ignoring segments of the population. Policy makers have a role to mitigate power imbalances through the use of well-balanced information sharing, proper engagement with public interest advocates, and participation and position rules.[3]

3 Participation rules set out which stakeholders are allowed to participate in the process and how they are selected. Position rules specify a set of roles within the stakeholders engaged with particular resources, privileges and responsibilities (for example, leading working groups referring to policy makers, or providing sector-specific reports).

Stakeholder engagement in the energy sector

Energy policies in particular have often been narrowly focused on specific topics such as energy supply and demand, price impacts, and emission reduction, without taking into account the broader socio-economic and environmental implications of energy production and consumption (IRENA, 2022g).

In the energy sector, stakeholder engagement is particularly important due to the complexity of the issues at stake. This complexity can create challenges for policy design and implementation, as different actors may have different priorities and perspectives on key issues. Moreover, the energy sector often involves multiple ministries and government agencies, as well as private sector actors, civil society organisations, and other stakeholders with different value systems and different concerns about specific aspects of the policies (IRENA, 2022f, 2023c).

Policy makers who decide to engage with stakeholders in drafting hydrogen strategies will also have the key role in organising the stakeholder engagement process, identifying the stakeholders and developing solutions to involve them. To avoid miscommunication and duplication of efforts, if the strategy is being drafted by multiple agencies, it is vital to be clear on who leads the process and is responsible for identifying and involving stakeholders. Stakeholder engagement and management at the earliest possible opportunity is recommended, especially to facilitate public acceptance (IRENA, 2021b).

The following sections put forth some solutions to engage with stakeholders when drafting hydrogen policies and strategies, proposing a way for identifying the potential stakeholders and their engagement tactics and offering some examples of stakeholders in the hydrogen sector.

3.2 The stakeholder matrix

To identify stakeholders and engage with all of them constructively and avoid power imbalances, it will be necessary to have a framework to classify them and understand how to engage with them. Policy makers will have to choose their preferred system and then act on the result of the analysis.

One option is the two-dimensional Eden and Ackerman matrix (Eden and Ackermann, 1998), which maps stakeholder groups and their interest areas onto a matrix. The grid is divided into four quadrants defining four categories of stakeholder based on influence and interest.[4]

Power: Stakeholders can have varying levels of influence on policy making depending on a number of factors: stakeholders with high levels of power, legitimacy and urgency are more likely to influence policy making than those with low levels of these factors. Power refers to the ability of a stakeholder to influence decisions and actions, and it can stem from a variety of sources such as financial resources, expertise or formal authority. Legitimacy refers to the perceived validity or appropriateness of a stakeholder's claims or actions, and it is often linked to social norms or values. Urgency refers to the degree to which stakeholders call for immediate attention (Mitchell, Agle and Wood, 1997).

4 The Eden and Ackerman matrix, while useful for mapping stakeholders based on influence and interest, has some limitations and is only a tool for early selection of stakeholders. The matrix, identifying only two characteristics of the stakeholders, may oversimplify the complexities and nuances of stakeholder relationships. It may not fully capture the dynamic nature of stakeholder engagement, as stakeholders' influence and interest can evolve over time. Another limitation is the potential subjective interpretation of stakeholders' influence and interest. Different perspectives and biases of policy makers or analysts may impact the placement of stakeholders within the matrix, leading to potential inaccuracies or misrepresentations. Additionally, the matrix may not account for the interconnectedness and interdependencies among stakeholders. Despite these limitations, a mapping exercise such as the Eden and Ackerman matrix serves as a starting point for stakeholder engagement.

Interest: Stakeholders' level of interest in a policy or project can influence their engagement and influence decision making. Stakeholders with a high level of interest may seek access to information and expertise that can shape policy outcomes, mobilise resources and organise collective action. This leads to four groups: the non-engaged (low interest – low power), the influencers (high interest – low power), the subjects (low interest – high power) and the key players (high interest – high power). The location of stakeholders in this matrix determines the strategy required to engage with them (Figure 9).

Figure 9 Stakeholder matrix

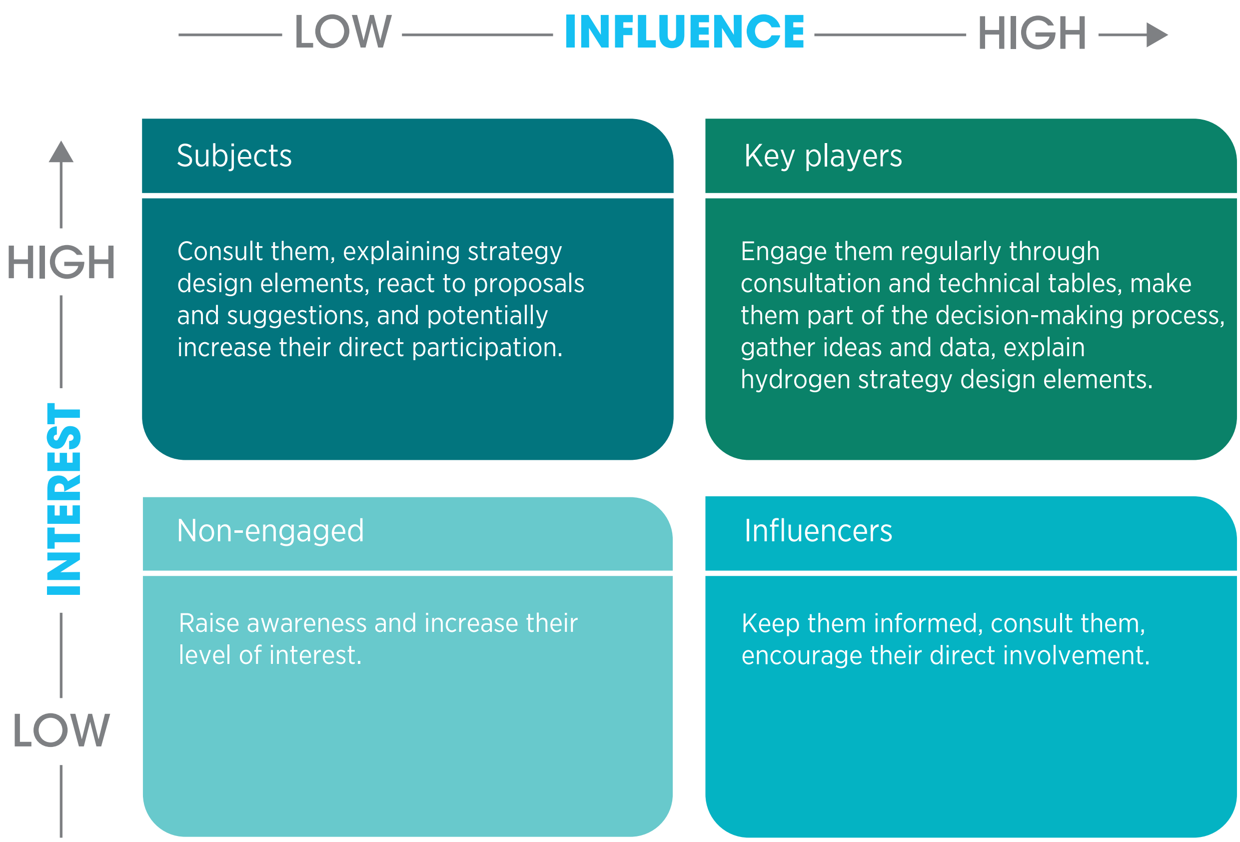


Table 1 Green hydrogen stakeholder identification and engagement tactic

<table>
<tr><th>Stakeholder</th><th>Influence</th><th>Interest</th><th>Engagement</th></tr>
<tr><td>Citizens</td><td>Limited</td><td>Limited, but potentially increasing with time

Provide public acceptance for the general sector

Fund support schemes</td><td>Should be included in the process with appropriate information channels; wishes and drivers of this group should be understood</td></tr>
<tr><td>Communities or Indigenous settlements affected by potential projects</td><td>Limited</td><td>High

Provide public acceptance for specific projects</td><td>Non-engaged to influencers

Should be included in the process and informed about the technology, benefits or disadvantages

Wishes and drivers of this group should be understood and taken into account to ensure acceptance</td></tr>
<tr><td>National authorities (not authors of the strategy)</td><td>High

Provide framework conditions in terms of regulations, tools and mandate</td><td>Limited to high, depending on the specific mandate</td><td>Subject to key players

Engaged based on national energy or industrial policy and drivers/frames for the hydrogen strategy</td></tr>
<tr><td>Local authorities</td><td>High

Provide the permits and licences to allow the project to proceed</td><td>High, if projects are to be developed in their area</td><td>Subject to key players

Engaged based on their level of efforts needed for permits and the impact of the projects in their areas</td></tr>
<tr><td>Electrolyser operators</td><td rowspan="3">Limited to high, depending on the strength of industrial associations</td><td rowspan="3">High</td><td rowspan="3">Key players and target group of the strategy – engaged continuously</td></tr>
<tr><td>Off-takers</td></tr>
<tr><td>Technology suppliers and project developers</td></tr>
</table>

Financial institutions	Limited to high Multi-lateral development banks may provide financing with policy change requirements	Limited to high Provide the finance and investment for the project, and recover investments	Influencers / key players Understand the evaluation criteria and priorities that govern the investment decisions
Investors	Limited to high		
Academia/ researcher	Limited Higher if enabled by specific regulation (*e.g.* standard setting) or to provide scenarios for the strategy itself	Limited, but they may provide knowledge about new emerging technologies, challenges and phenomena	Influencers to be engaged, such as through research-action projects
Utilities	High	High	Key players to engage continuously
Power system transmission and market operators	High	High	Key players to engage continuously, in particular for planning purposes
Oil and gas companies, including gas transmission and distribution system operators	Limited to high, depending on various local factors	High	Influencers or key players, depending on their influence To inform and engage depending on their real commitment to decarbonisation

After stakeholders have been identified, the next step is to actively involve and engage them in the hydrogen strategy making process. The nature of stakeholder engagement could be as follows:

- **Collaborative decision making:** Involving stakeholders in the hydrogen strategy making process, particularly by allowing the presentation of proposals for the strategy content to the government. Establish mechanisms for collaborative decision making, such as working groups or committees that include representatives from different stakeholder groups (Box 5), so as to provide the opportunity for stakeholders to actively contribute to the development of the strategy, including defining targets (section 7) and identifying implementation measures (section 9).

- **Open and transparent communication:** initiating a dialogue with all the stakeholders to explain the goals, objectives, and benefits of the hydrogen strategy, sharing information about the potential impact of the initiative and addressing any concerns or questions they may have. Through a bilateral communication, it is possible to identify and articulate how stakeholders can benefit from the development of a hydrogen sector, allowing policy makers to highlight these positive impacts in the strategy.

By implementing these actions, stakeholders can be effectively engaged and become active participants in the process. Their involvement will contribute to the development of a robust and inclusive strategy that addresses their concerns, incorporates their expertise and maximises the benefits for all involved parties.

Box 5 Chile's participatory approach in its green hydrogen strategy

Chile's hydrogen strategy provides a good case study for collaborative governance and strategic planning. Central to this approach was a gradual and inclusive participatory process involving various stakeholders, which helped shape a comprehensive roadmap for the sector's growth.

Chile's stakeholder engagement consisted of a series of interactive fora and initiatives (Figure 10), each engaging distinct profiles of participants, allowing a gradual enhancing and focusing of the strategy.

In the **Interinstitutional Roundtable** (four sessions between April and October 2020), public stakeholders – including government ministries such as energy, science, technology and mining – engaged in discussions to refine the industry's diagnosis, objectives, and vision, ensuring alignment across government bodies. This roundtable was an opportunity to gather the key players from Chile.

This was complemented by an **Advisory Board** to the Ministry of Energy (four sessions between April and October 2020) that gathered public policy and climate action experts. The board provided high-level strategic advice, assisting the Ministry of Energy in shaping the public policy.

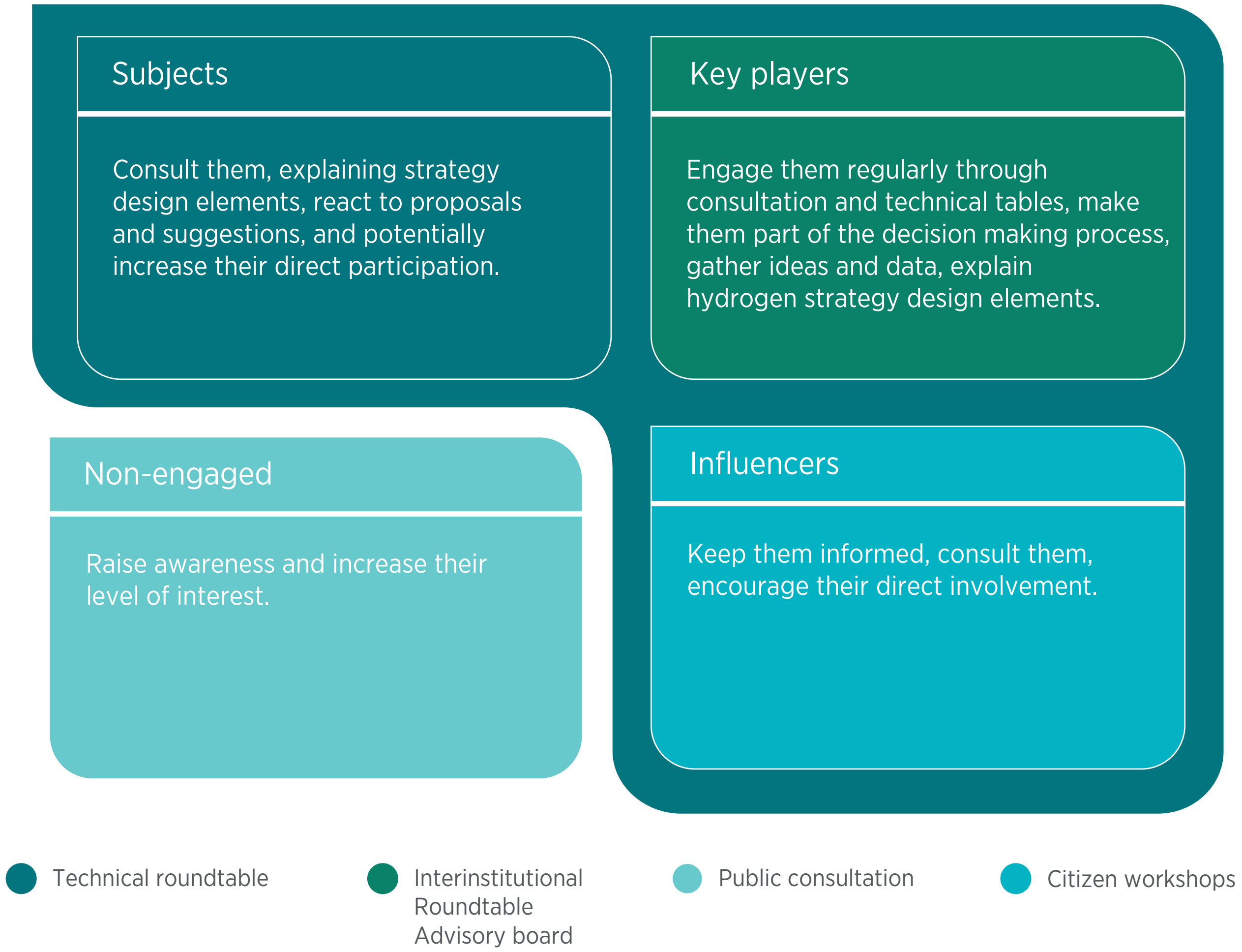
Technical Roundtables (June and July 2020) involved 66 organisations, providing a platform for companies, universities, research institutions and industry associations. Their contributions helped identify barriers and prioritise solutions for hydrogen development. These roundtables were an opportunity to gather knowledge from subjects, influencers and key players.

Citizen Workshops engaged representatives from non-governmental organisations and citizen associations (influencers) in three sessions during August 2020. These interactive workshops allowed local concerns and perceptions regarding the state's role in green hydrogen development to be voiced and considered.

A public consultation of a first draft of the document was held in November 2020 to ensure that the broader public had an opportunity to provide input and feedback on the developing strategy, engaging with the possible non-engaged.

By engaging diverse profiles of stakeholders and experts in various participatory fora, the Chilean government managed to inform and be informed by its citizens, at any level of influence and interest.

Figure 10 Stakeholder engagement in the Chilean strategy making



4. How to integrate the strategy in the energy planning? Long-term energy scenarios

More than 100 years ago, in December 1920, the government of the Soviet Union adopted the first state electrification plan, GOELRO, which aimed to increase the capacity and generation of power plants several times during a 10-15 year period (Makarov, 2020).

Since then, long-term energy scenarios (LTES) have been used as important energy planning tools for setting targets and informing stakeholders. These scenarios provide a clear roadmap for achieving long-term goals, tailoring to each country's unique context, encompassing various aspects such as energy production, transport, final energy consumption, and import or export dynamics. Examples of the use of LTES include low-carbon development strategies, industrial decarbonisation strategies and energy security strategies. LTES are a well-established planning tool for governments to explore the possible evolution of energy systems and to equip decision makers to understand the complex inter-relations and uncertainties surrounding these systems.

National hydrogen strategies are closely intertwined with LTES. Leaving a hydrogen strategy disconnected from other programmatic documents may hinder the overall coherence and effectiveness of a country's energy transition efforts. If a hydrogen strategy is developed in isolation and not aligned with programmatic documents, it may result in fragmented decision making, duplication of efforts, and missed opportunities for synergy and collaboration.

For example, a disconnected hydrogen strategy may overlook the potential synergies between sectors, such as transport or industry, where hydrogen can play a significant role in decarbonisation. It may fail to consider the integration of clean hydrogen production and infrastructure planning within the broader energy system, leading to sub-optimal deployment and inefficiencies. Additionally, a lack of alignment with programmatic documents can hinder policy coherence and co-ordination, making it challenging to secure the necessary investments, regulatory frameworks and stakeholder engagement needed for successful implementation.

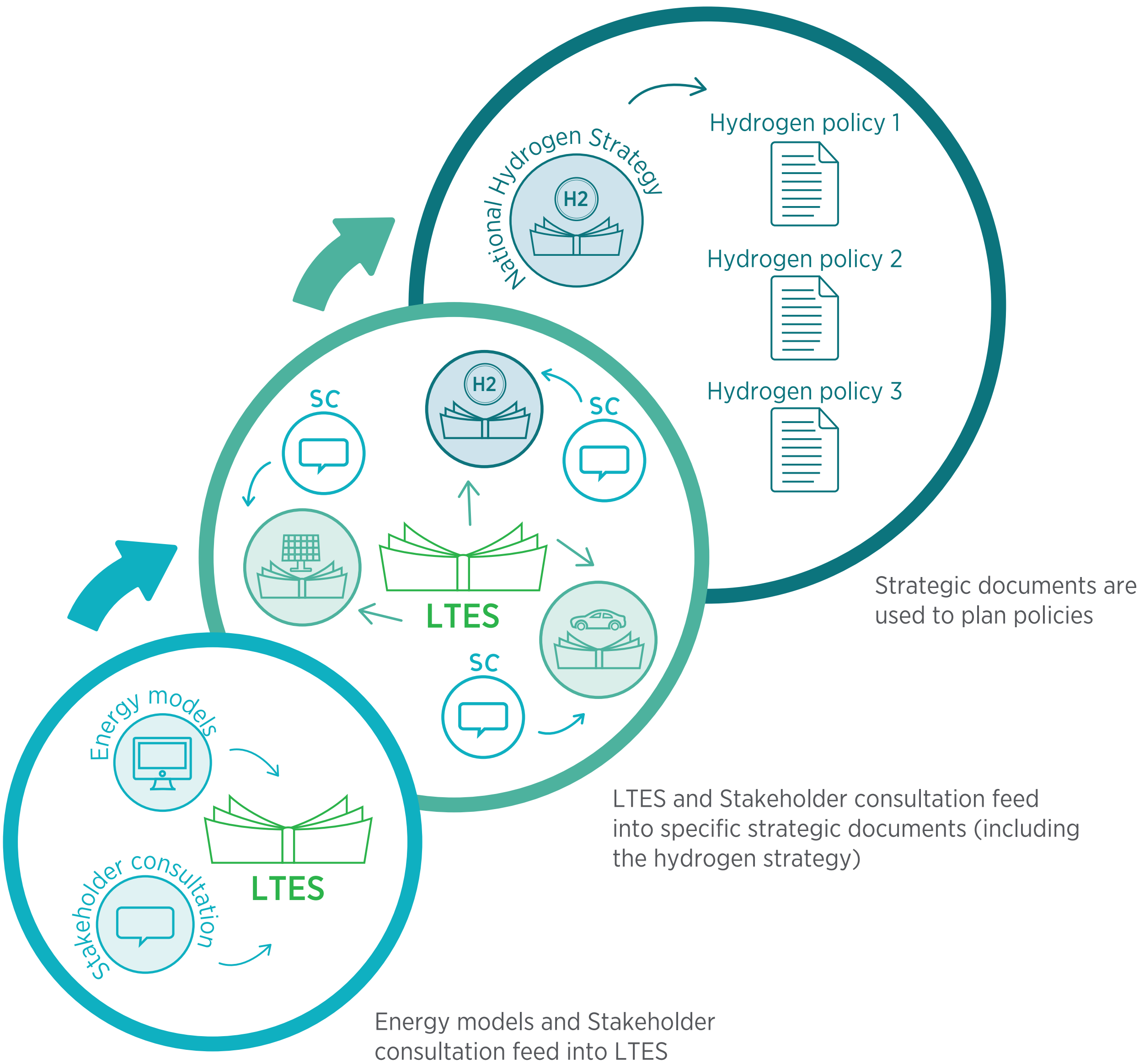
To avoid these risks, it is crucial to ensure that a hydrogen strategy is developed in conjunction with or integrated into existing programmatic documents. This approach allows for a holistic and co-ordinated approach to energy transition, leveraging the synergies among different strategies, minimising efforts by policy makers and maximising the impact of hydrogen as a clean energy carrier. By aligning the hydrogen strategy with programmatic documents, countries can enhance policy coherence, facilitate cross-sectoral collaboration, and create a cohesive roadmap for achieving their long-term energy and climate goals.

4.1 The correlation between models, LTES, hydrogen strategies and other documents

Ideally, a hydrogen strategy results from a series of interconnected documents developed with modelling tools and stakeholder engagement.

Energy modelling tools[5] are a first instrument; they help to quantify the implications of using different technologies within an energy system and their linkages with other sectors. They feed LTES that then can be used in policy making (Figure 11). The qualitative aspects of LTES – such as visions, storylines, and plausible evolution of technologies and markets – are formed through stakeholder consultation in the LTES development process (see section 3).

Figure 11 Representative: from modelling to policies



5 Energy models are the mathematical representation of an energy system or part of an energy system; they are developed to analyse or solve various problems related to energy consumption, supply and transformation. The energy models can be categorised as top-down, bottom-up and hybrid. A variety of energy modelling tools are available (both commercial and non-commercial); the selection of the most suitable tool (or tools) for the LTES should be based on strategic decisions.

LTES serves as a starting point for a hydrogen strategy that needs to be updated in regular cycles, introducing new elements as the technology evolves and the map of energy exchanges mutates.

Starting from LTES, other documents can be developed such as sectoral strategies, an industry decarbonisation strategy and documents outlining how to maintain energy security in the context delineated by the LTES. The scope of these documents (including the hydrogen strategy) is to provide a deep-dive vision on a specific question or topic, given the future planned in the LTES. All these documents feed each other. For example, it would be unwise if the plans for industrial decarbonisation do not match the use of hydrogen in industry foreseen in the hydrogen strategy. Stakeholder consultation is also vital in this phase.

From these documents, it becomes possible to determine what policies and measures are needed to achieve the plan delineated in the strategies.

Under this context, LTES can support policy makers to frame a well co-ordinated and effective national hydrogen strategy, in a variety of ways.

Firstly, LTES helps in establishing a starting point or "beacon" for integrating the country into global hydrogen value chains. It allows policy makers to envision the future role of clean hydrogen in the energy mix and to plan accordingly, considering factors such as production, distribution and use.

By conducting comprehensive analyses for LTES, policy makers can identify key drivers that will shape the growth of the hydrogen sector. LTES can also support the establishment of national and sectoral priorities to stimulate hydrogen demand effectively. By assessing LTES and quantifying their impacts, policy makers can prioritise specific sectors where green hydrogen can have the greatest impact (see section 5). This prioritisation guides policy decisions and resource allocation, ensuring that efforts are focused on areas that will yield the most significant benefits for decarbonisation and the energy transition.

Additionally, LTES facilitates the enhancement of governance frameworks surrounding the green hydrogen sector. It enables internal co-ordination among various government agencies and stakeholders, ensuring cohesive decision making and effective implementation of regulatory frameworks and policies. Moreover, LTES may help to create a basis to attract new investments by providing a clear and quantified roadmap for green hydrogen development. Policy makers can present calculated risks and opportunities to potential investors, fostering a favourable investment climate and accelerating the growth of the green hydrogen sector within the country.

4.2 Technical representation of green hydrogen in LTES

The starting point to incorporate elements of green hydrogen development into LTES is understanding what parts of its value chain fit in the country's energy transition landscape, while aligning with the broader national strategies and final purpose of the energy scenario (previously defined in the stakeholders' co-ordination and consultation steps). This intersection of perspectives will identify the elements of green hydrogen development that should be assessed in the LTES and determine the critical decision parameters for the strategy.

The representation of green hydrogen in LTES can be done in a quantitative or qualitative approach. Hydrogen and its derivatives are more frequently represented using quantitative approaches in the production and consumption links of the hydrogen value chain, whereas for the transport and storage link, qualitative approaches are more common. This difference in representation of hydrogen elements in scenarios can have various causes – for example, the purpose of the scenario, or the (lack of) data availability (IRENA, 2023c).

Different types of energy models can be used to incorporate hydrogen in the LTES, but to consider the broader impacts of hydrogen scale-up, support sustainable development, and ensure long-lasting strategies, energy models able to perform multi-sectoral or integrated analysis of the energy systems should be preferred.

To develop effective green hydrogen strategies, policy makers should consider various aspects. Firstly, policy makers should include regional or sub-regional resource assessments to evaluate the renewable potential of their countries, supporting the production of green hydrogen. These assessments will provide insights into the available renewable resources that can serve as a foundation for hydrogen production, contributing to the overall viability and success of the strategy (Box 6).

Additionally, policy makers should decide (at least in a preliminary manner) to what extent green hydrogen production will be off-grid versus on-grid or both, as each option has different implications for the overall energy system. Analysing the on-grid option requires considering the reliability and security of power systems, as well as the potential for electrolysers to act as flexibility mechanisms, especially in the context of the increasing share of VRE on the supply side of power systems and the growing request for power system flexibility resources.

Moreover, when constructing integrated models for hydrogen and its derivatives, policy makers should consider existing energy infrastructure, the required form of hydrogen, renewable resource assessments and the co-products generated during transformation (such as heat, oxygen and methane). This assessment will help determine the optimal locations for hydrogen production based on factors such as proximity to demand or production areas, impacting the overall cost and rationale of the strategy.

Box 6 Green hydrogen potential

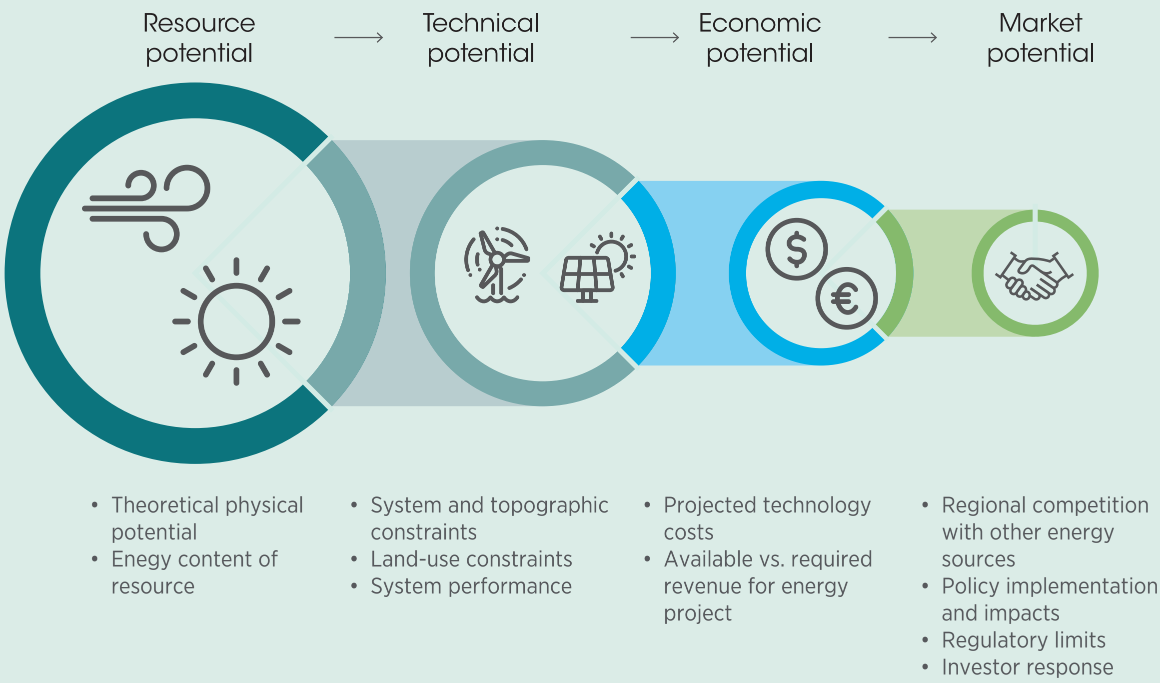
The assessment of green hydrogen production potential in a country is similar to assessing renewable energy potential. It can be broadly divided into four stages: resource potential, technical potential, economic potential and market potential (Figure 12).

However, the boundaries between these stages are often blurred due to numerous uncertainties and a lack of consensus in definitions. Among these uncertainties are contradictory trends in the reduction of costs for relevant technologies (for example, electrolysis), unclear possibilities for necessary infrastructure (electricity, water, pipelines, underground CO_2 storage for blue hydrogen, etc.), as well as extremely uncertain prospects for demand for hydrogen and its derivatives within the country and beyond. The differences between these stages are determined by the set of uncertainties taken into account.

For green hydrogen:

- Resource potential is determined by the theoretical potential of renewable energy sources (which depends solely on geographical conditions).
- Technical potential is lower, considering land limitations, issues with electrical grid infrastructure, or water stress.
- Economic potential is even lower, taking into account the cost of relevant technologies.
- Market potential is the smallest among the four stages because it is influenced by market constraints within and outside the country, including investor behaviour and institutional capacity.

Figure 12 Types of renewable energy potentials



The assessment of hydrogen potential in Central Asia, the Caspian region and Eastern Europe exemplifies the set of these uncertainties and their impact on the final assessment result (UNECE, 2023).

In global models that evaluate hydrogen production potential and prospects for international trade, countries in these regions may be ignored or considered only as potential importers (Hydrogen Council and McKinsey & Company, 2022; IRENA, 2022c, 2022e). However, policy makers in Azerbaijan, Kazakhstan and Uzbekistan consider the possibility of exporting hydrogen to the EU and other markets.

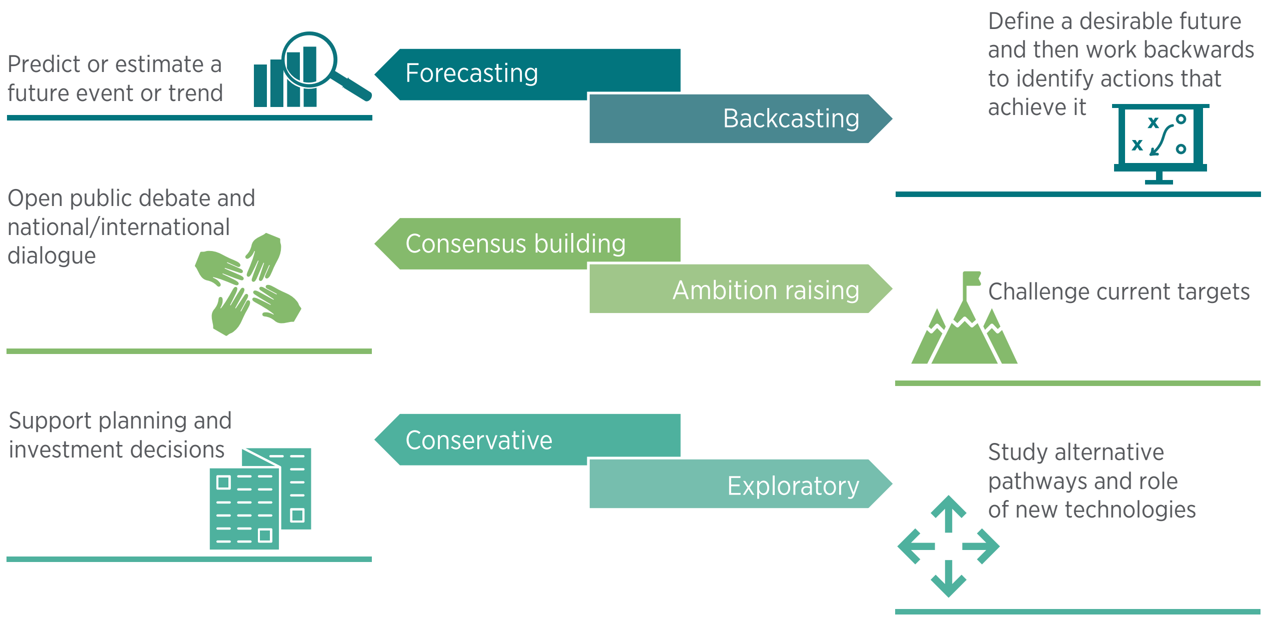
The combined clean hydrogen production potential in nine countries of Central Asia, the Caucasus and Eastern Europe by 2040 ranges from 3.4 megatonnes (Mt) to 13.2 Mt per year (UNECE 2023). The four-fold range between the minimum and maximum boundaries is determined by a set of uncertainties related to renewable energy development (considering the need for power sector decarbonisation); low-emission gas production potential in the upstream phase; the development of carbon capture, utilisation and storage (CCUS); and other factors.

The study suggests that the pace of the hydrogen sector in different countries will depend less on their available resources and more on strategic emphasis on low-carbon development, suitable regulations, market expansion, technology advancement and international co-operation. This may involve efforts to standardise hydrogen and related technologies globally, implement joint projects and adopt a shared export strategy.

4.3 Purpose of LTES to support green hydrogen strategies

In the context of developing a hydrogen strategy, the primary purpose of LTES is to provide an idea of how the energy system could evolve and respond to different conditions of hydrogen production and consumption. However, there are other uses of LTES, as depicted in Figure 13.

Figure 13 Common uses of long-term energy scenarios



Source: (IRENA, 2020b).

Policy makers involved in developing green hydrogen strategies should carefully evaluate the most common uses of LTES to determine which can provide the most value in supporting the objectives and purposes of their respective hydrogen strategy.

Forecasting: This is used to estimate a future condition or trend that may affect the energy system. For hydrogen strategy, the LTES can be used to estimate future hydrogen demand and production in the country, including the electricity required to produce this expected demand, assess different options to supply this electricity (on-grid capacity, off-grid capacity), estimate future investment needs and estimate the greenhouse gas mitigation impacts. Given all the objective limitations in accuracy forecasting in the rapidly evolving landscape of new technologies and constantly (and sometimes spontaneously) changing external conditions, scenario planning allows at least for the boundaries of possible changes in forecasted parameters to be addressed and, based on these scenarios, for the formulation of a strategy.

Backcasting: This involves setting a desirable future condition, target or policy goal and then assessing different backward pathways to identify the actions and governmental interventions needed to achieve it. This approach helps to answer "*what-if*" questions and has been seen to be the most common use of scenarios to assess the cost effectiveness of different development pathways (in particular in a net zero context). Green hydrogen policy makers can use LTES to find feasible pathways to reach a particular target for hydrogen development and to identify needs for new policies, regulations, or investments, or complementary strategies to support its development. In general, by asking *how we can achieve a specific condition in the future* helps to better understand the implications of taking one decision or other. This approach can also complement the **phases approach**

(see section 9) taken by decision makers when designing this type of strategy – that is, dividing the planning horizon up to 2050 into two to three phases. Then, backcasting using LTES can be helpful in the initial phases where the foundations of the hydrogen strategy are created.

Consensus building: Engagement with different groups of stakeholders is an essential aspect of the strategy development, and green hydrogen policy makers can use the insights provided by LTES as a starting point to initiate public debates and national or international dialogues with different groups of stakeholders (companies, citizens or research centres). These debates can support the development of a hydrogen strategy in setting unified (yet preliminary) long-term visions, establishing national priorities, integrating other national concerns into the strategy, and harmonising existing policies and strategies to guide the formulation of a well co-ordinated hydrogen strategy.

Ambition raising: The cross-sector nature of LTES allows green hydrogen policy makers to incorporate improved assessments of existing infrastructure and energy supply and demand balances, renewable energy potential, technology cost trends, and sector coupling to devise more ambitious and realistic pathways to produce and consume green hydrogen (and its derivatives).

Support planning and investment decisions: Whether LTES are used for forecasting or backcasting purposes, they can play a role to estimate future investments for production, transport and consumption infrastructure.

Exploratory: in this case LTES are used to study extreme alternative pathways and the role of new technologies. This approach is usually taken for research purposes, and more ambitious scenarios with stringent measures are preferred. This approach can support hydrogen strategy in making stress tests and explore the impact that critical conditions might have on the strategy.

As presented, LTES can have several purposes in designing the strategy, and sometimes, a combination of approaches can be pursued; in the end, it will depend on the country's specific conditions.

With the emergence of hydrogen as a key energy carrier, hydrogen strategies have become a new component within the broader framework of strategic planning. LTES facilitate an integrated understanding of the complex relationships and uncertainties within energy systems. By exploring different future pathways, LTES equip decision makers with insights to navigate the evolving hydrogen value chain and to develop comprehensive hydrogen strategies and roadmaps.[6] Examples of links between LTES and hydrogen strategies are not uncommon (Box 7).

6 IRENA is deeply involved in the topic. IRENA's LTES Network is the global platform to exchange knowledge and best practices on the development and use of energy scenarios between experts from governmental energy planning institutions and between them and other experts on energy scenarios or technical institutions that support countries in energy-related aspects. Up to 2023, the LTES Network has collected and synthesised experiences and practices from over 50 countries to understand how they are using scenarios to support the development of specific policies, plans and strategies.

Box 7 Examples of LTES and hydrogen strategy co-ordination

Beyond representation in energy scenarios, co-ordination among developers of energy and climate strategies with developers of hydrogen strategies and roadmaps is essential to unify signals for policy makers and investors to identify how hydrogen targets can be achieved on the national level.

For instance, the **Belgian** strategy references the Belgian LTES about the expected growth in hydrogen demand. Similarly, **Denmark's** strategy mentions the scenarios from its national electrification strategy, ensuring that there is alignment with broader electrification objectives.

The **Chilean** strategy was based on a set of LTES developed by the Ministry of Energy that provided insights on the possible evolution of Chile's energy sector, considering aspects of economic growth, energy demand, technology developments and climate neutrality objectives. These LTES informed about the quantity of green hydrogen needed in Chile to achieve a carbon-neutral scenario. The LTES of Chile also informs policy makers about important elements that will enable the energy transition. For example, electrification of different energy uses provided by fossil fuels today requires electrical grids that are not only reliable but also resilient, as well as a strengthening in the electricity quality of service. Those electrical grids will also allow the production of green hydrogen in non-merchant settings.

The **Spanish** strategy was based on a detailed scenario analysis of the potential of green hydrogen in the country. This analysis was conveyed with a set of specific energy models and modelling tools to analyse the evolution of the energy system, guarantee energy security, and estimate the socio-economic and emissions impacts on the overall economy (including energy and non-energy sectors).

If a strategy is published before a LTES, it can be used to inform the latter: **Germany's** scenario study for its National Energy and Climate Plan refers to the Hydrogen Strategy. The study provides a comprehensive comparison of its scenarios to the Hydrogen Strategy, giving stakeholders clarity on the broader energy landscape.

PART 2

Setting objectives

5. What first?
Priority setting

Once the decision to promote green hydrogen has been made, policy decisions include what applications should be prioritised and how quickly to make the shift from fossil fuels to green hydrogen. This implies the action of priority setting, which refers to the process of identifying and ranking the key technologies that should receive the most focus and resources first.

The priority-setting action in national hydrogen strategies can be applied in all three main parts of the value chain: upstream (what kind of hydrogen production pathway is going to be supported?), midstream (what system to transport hydrogen will be developed first?) and downstream (what end uses of hydrogen will first become reality?).

Technically, hydrogen can be used in many different sectors. However, despite its great potential, the production, transport and conversion of hydrogen require energy and significant investment (IRENA, 2021a, 2020c). Moreover, despite hydrogen's great promise and its suitability to replace fossil gases, it is not the only substitute for fossil fuels nor the sole solution for achieving net-zero goals. Instead, it is just one of several possible decarbonisation alternatives (IRENA, 2020a, 2020c) that should be carefully weighed when setting priorities.

There are several reasons why priority setting is crucial in national hydrogen strategies:

1. Priority setting can help create a clear roadmap for deploying hydrogen technologies. It provides a vision of where a country wants to go and how it plans to get there. This helps to create certainty for investors and other stakeholders, who need clear signals about the direction of policy and the likely future demand for hydrogen technologies. A well-defined roadmap can help to attract private sector investment and drive innovation in the sector.
2. Developing a hydrogen sector requires significant investment, and it is crucial to sensibly allocate resources (financial but also political capital). Priority setting allows policy makers to identify the areas where investing makes the most sense with less regret.
3. Concentrating resources on priority areas (or obvious end use choices) can also accelerate the deployment of hydrogen technologies, reducing the overall time and resources needed to achieve results. Time is a critical resource: just over 25 years are remaining until 2050, which is comparable to the lifespan of most projects in the energy sector, and there is very little time left to achieve the goals by 2030.

4. Prioritising areas could accelerate cost reductions and the scalability of the selected technologies, making them more accessible and competitive in the marketplace.
5. Priority setting helps to ensure a coherent and consistent approach to deploying hydrogen technologies, which matters since the hydrogen sector will involve multiple stakeholders (IRENA, 2020). It is also particularly relevant for countries with federal systems. Without a clear set of priorities, there is a risk of fragmentation and duplication of efforts. By setting priorities, stakeholders can align their efforts and resources towards common goals, leading to a more co-ordinated and effective deployment of hydrogen technologies.

5.1 Factors influencing priority setting

Priority setting for green hydrogen strategy relies on assessing different factors. Some of these factors can be similar among countries globally, while others are country- or region-specific. Factors influencing priority setting can be determined by global developments in hydrogen technologies, by domestic aspects of a country, or by its foreign policy and economic relations. However, the vast majority of factors pertain to the domestic aspects of the country, such as the country's resources, geographical characteristics, and level of technological and economic development. These factors are fairly evenly distributed across the upstream, downstream and midstream sectors. Thus, priority setting is determined primarily by the internal specifics of a country and involves all segments of the hydrogen value chain.

Therefore, the elements used to justify priority setting in national hydrogen strategies will vary based on the unique circumstances of each country. The key is to identify the areas where the investments of financial or political capital make more sense and will bring less regret. Countries that have published hydrogen strategies typically use a combination of elements, such as those outlined in Table 2, to identify and justify their priorities, which are presented in Table A4.

Table 2 Factors influencing priority setting

Factor	Upstream	Midstream	Downstream	Notes
Global development of hydrogen technologies				
Technology Readiness Levels (TRLs)	X	X	X	TRLs are a measure of the maturity of a technology. They are important in the context of national hydrogen strategies because they can influence priority setting for investment and deployment. Countries with limited R&D facilities may prioritise the development of technologies with higher TRLs, as these are closer to commercial deployment and have a lower risk of failure. On the contrary, countries with potential for hydrogen R&D may also prioritise the development of technologies with lower TRLs, as these may represent breakthrough technologies with significant potential for cost reductions or improved performance and could provide additional benefits of industrial competitiveness in the future.

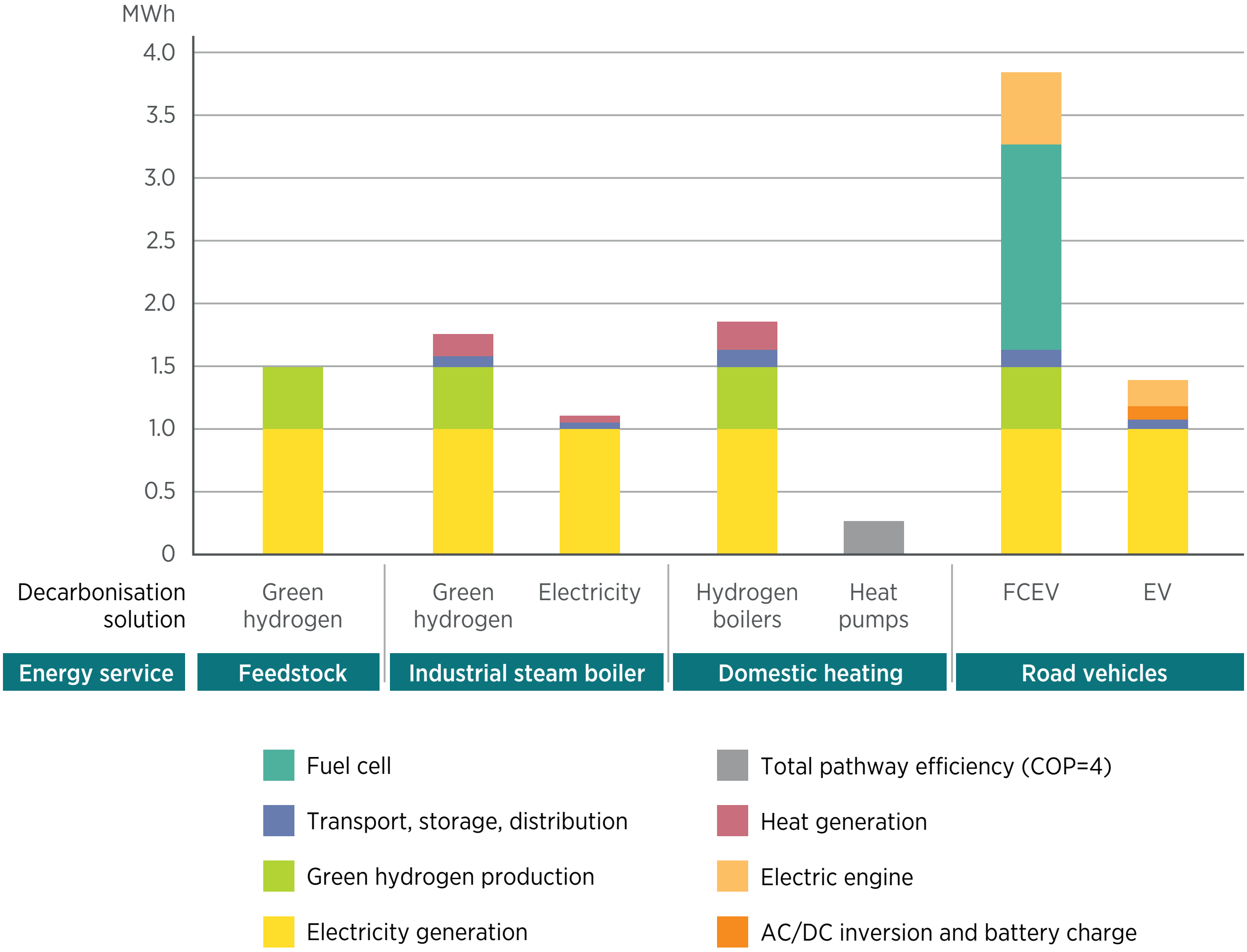
TRL (comparison between alternatives)	X		X	Another way to assess TRL is by comparing the TRL of hydrogen technologies versus the TRL of other decarbonisation solutions, to identify, for example, when electricity is a best solution or when hydrogen would be a more immediate one.
Cost of alternatives (including life-cycle basis)		X	X	Competing decarbonisation alternatives have different capital and operating costs (CAPEX and OPEX), which can drive the choice to support certain technologies over others.
Electricity consumption	X		X	When electricity-based alternatives are available, the electrical efficiency pathway metric can be used to assess how much more electricity the use of hydrogen would entail compared to direct electrification. Solutions relying on the direct use of electricity consistently consume less energy than hydrogen-based alternatives (see Figure 5.1), and the size of the difference can inform policy makers about the estimated additional power capacity needed to supply a certain sector with green hydrogen (IRENA, 2022a). However, hydrogen solutions may be favoured by other factors, such as seasonal imbalance or remoteness of specific loads.
Large-scale, long-term energy storage and transport		X		Large-scale, long-term energy storage is currently achieved only through the molecules of fossil fuels. Hydrogen and derivatives can be provider of these services (see section 2).
Domestic aspects of the country				
Resource availability	X			The availability of fossil fuel reserves, nuclear energy (and the nuclear fuel cycle), land, water resources and renewable energy sources in a country determine the interest towards a certain production pathway.

Current assets	X	X	X	Present industry, assets and manufacturers may drive priority setting. A strong manufacturing industry for hydrogen components may lead to prioritising the development and deployment of these components. Current natural gas distribution and transmission pipelines and seaports may act as blueprints for future hydrogen infrastructure. Vice versa, a lack of these assets allows more flexibility in system planning. The targeted uses may depend on the existence of hydrogen demand, such as basic chemical industries. In sectors such as steelmaking, aviation, and maritime transport, there is significant potential for the use of hydrogen to reduce carbon emissions. Countries with globally competitive industries that can be impacted by hydrogen transformation can prioritise these industries to maintain long-term leadership. Countries with a high share of renewable energy sources and nuclear power in the electricity sector (Norway, Sweden) are less interested in stimulating the use of hydrogen for power generation compared to coal-dependent countries (Japan, Republic of Korea).
Patents	X	X	X	Patents are a valuable form of intellectual property protection that can provide a competitive advantage to companies that hold them. As a result, countries with a high concentration of patents in the hydrogen industry may prioritise the development, deployment and export of technologies that are covered by these patents. In addition, the presence of patents can influence the choice of technology that a country prioritises in its hydrogen strategy. For example, Japan and the Republic of Korea prioritise the development of fuel cell technology since they hold a significant number of patents in this area.This may be done to ensure that the country can leverage its intellectual property to gain a competitive advantage in the global market for hydrogen technologies.
Seasonality of VRE production		X	X	Large seasonal variability of VRE generation may push policy makers into prioritising hydrogen storage and applications

Centralisation			X	The kick-start of the hydrogen sector can benefit from economies of scale in large demand centres, making the transition even more cost effective as compared to distributed or novel applications. Large, consistent and long-term demand allows hydrogen production to expand, lowering costs and allowing for even wider use. As a result, "hydrogen valleys" are a viable alternative for boosting regional hydrogen demand. Hydrogen valleys are usually large in scale (setting up two-digit multi-million USD investment) and have high value chain coverage (covering multiple steps of the value chain), supply of more than one sector and a geographically defined scope. As of January 2024, 30 countries had a total of 89 ongoing Hydrogen Valley activities (Clean Hydrogen Joint Undertaking and Mission Innovation, 2024).
Socio-economic considerations	X	X	X	The potential for hydrogen technologies to contribute to economic growth and prosperity is an important factor in decision making. The deployment of hydrogen technologies can create new jobs, also with the reskilling of the fossil fuel workforce. Policy makers may consider prioritising the development of local supply chains, promote the use of local labour and resources, and ensure that vulnerable groups are not left behind.
Creation of a hydrogen market			X	For countries with abundant fossil fuel reserves, there may be an interest in creating a large hydrogen market so that blue hydrogen is going to be needed, as renewable energy deployment cannot follow the large demand increase (if methane emissions are kept low and the carbon capture rate is high).
Decentralised areas	X	X	X	Decentralised areas, such as islands or remote villages, present unique challenges in energy supply and distribution. In the context of national hydrogen strategies, the presence of decentralised areas can reshape priorities towards the development and implementation of hydrogen technologies that are suited to the specific needs of these areas. This may include the development of small-scale hydrogen production facilities and the use of FCEVs for transport.
Supply diversification	X			Countries with high energy import dependency may decide to allow any hydrogen production pathway to ensure supply.

Country’s external environment				
Geopolitical considerations	X	X	X	Geopolitical considerations can play a significant role in the priority setting of national hydrogen strategies. For example, countries with significant natural gas reserves and well-established gas infrastructure may prioritise the development of blue hydrogen production, with carbon capture and storage (CCS) technologies, to maintain their historic role as energy exporters. On the other hand, potential trade tensions and political instability could lead to the consideration of green hydrogen as a means of energy security for energy importers. Diplomacy, shifts in political relations, concerns about import dependence and exposure to international price volatility, and a desire to improve flexibility and resilience may shape trade routes and pipeline projects. Geopolitical considerations can impact the prioritisation of hydrogen applications as well. For example, countries with a strong fuel cell industry may prioritise the deployment of hydrogen FCEVs to compete with countries that have invested in battery electric vehicles and support the internationalisation of such technologies.
Industry attraction			X	Since the Industrial Revolution, industry has tended to relocate where cheap resources are available. Countries, particularly in the Global South, have the opportunity to prioritise the relocation in their boundaries of industries such as basic chemical and steel makers that would benefit from cheap green hydrogen (UNIDO, IRENA and IDOS, 2023).
Supply chain security	X	X	X	The reliable and efficient delivery of hydrogen technologies, equipment and materials is a critical determinant of the success of hydrogen projects. Supply chain security may be particularly important in the context of reducing long-term foreign dependency, considering economic or political risks. Examples from other industries are indicative: China controls at least 75% of every key stage of solar photovoltaic panel manufacturing and processing across the globe, while the Russian Federation controls 38% of the world’s uranium conversion capacity and 46% of uranium enrichment capacity, in addition to decommissioning and waste disposal. Prioritising supply chain security in a country’s strategy can help avoid these risks. For instance, “spur domestic manufacturing and robust supply chains” is one of the eight guiding principles in the draft US National Clean Hydrogen Strategy and Roadmap.

Figure 14 Estimation of renewable electricity generation needed for 1 megawatt hour, by energy service and transformation passage



Source: (IRENA, 2022i)

Notes: AC = alternating current; DC = direct current; EV = electric vehicles; FCEV = fuel cell electric vehicles.

5.2 In focus: "Silver bullet" or "champagne"?

The selection of the priorities (and the elements that drive the selection) differ notably among published national hydrogen strategies. Two polarly different views can be highlighted: the "silver bullet" and the "champagne".

The "silver bullet" approach sees hydrogen as a potential solution for all sectors where it could be applied, from the chemical industry to residential heating. This view considers the risk of climate change to be too high to exclude any option. The approach usually has a strong "free market" attitude, so it discourages excessive interventionism in selecting where hydrogen should be consumed and sees the role of policy makers as facilitators to ensure demand and supply alignment and market creation. Due to this, midstream interventions to make transport of hydrogen possible in early stages are more prominent in this approach.

The “silver bullet” approach is more common in strategies from Global North countries that are also producers of fossil fuels, such as Australia, Canada and the United Kingdom (Box 8). In these countries, possibilities of blue hydrogen production for local use and export enables the discussion around how to increase the future role of clean hydrogen. This approach is not common among fossil fuel exporting countries in the Global South, which operate mainly on the rentier economy model, with strong dependency on revenues from fossil fuel exports (although some countries, such as the United Arab Emirates, have achieved impressive results in moving away from this model).

Conversely, countries of the Global North have long been developing under the model of a production economy. They have had access to technologies and finance for decades, which has allowed them to greatly reduce the energy and carbon intensity of national economies and even achieve decoupling of energy use and economic growth. For a long time, these countries have been developing clean energy and the whole set of decarbonisation solutions, and hydrogen is becoming a reasonable pathway for them – since they are already successfully using the rest of the set. The “silver bullet” approach is more applicable in conditions where stakeholders discuss bans on internal combustion engines or ways to fully decarbonise the building stock energy supply within 15 years, opening the discussion of whether hydrogen blending or equipping all buildings in the country with heat pumps is better.

The “champagne” view is more cautious and considers green hydrogen to be too expensive, and large-scale investment too risky, compared to the alternatives. It envisages a very specific role for green hydrogen only where other options are unavailable. The champagne approach frames the energy transition as an urgent task, for which it is unwise to attempt unproven technologies to the detriment of proven ones. This view could be seen as an industrial policy, with interventions aimed at guiding and controlling the structural transformation process of an economy. It is proposed mostly by countries – such as Austria (Box 9) and Kenya – that have good renewable energy resources and the potential to make existing industry greener or to achieve green industrialisation.

The “champagne” and “silver bullet” approaches represent two extremes in a spectrum of options to loosely categorise the published strategies of various countries, as summarised in Table 3.

Table 3 Silver bullet and champagne approaches

Silver bullet	Champagne
• Clean hydrogen can be used in any end use and should be enabled to do so when competitive. • The risk of climate change is so high and urgent that we cannot leave any option behind. • Policy makers’ role is to make hydrogen use possible everywhere in the region. • This reflects a “midstream approach”, with priority on making pipelines hydrogen-ready and supporting all decarbonisation solutions.	• Clean hydrogen is too expensive, and investments too risky, to be used everywhere. • With climate change, we have less than 30 years and there is no time to experiment. • Policy makers’ role is to accelerate the hydrogen transition for end uses where there are no real alternatives. • This marks the return of industrial policies and higher control over the allocation of financial and political capital on the hydrogen choice.

Box 8 Example of the "silver bullet" view: the UK Hydrogen Strategy's support for diverse end use applications

The UK Hydrogen Strategy stands out for covering a broad spectrum of hydrogen applications, expected to be achieved by the late 2020s to mid-2030s. The strategy envisions supporting research, innovation and commercialisation of hydrogen technologies across diverse end use applications, as well as testing and industrial-scale deployment to overcome barriers hindering low-carbon hydrogen alternatives. The approach empowers the market, not regulators, to determine the optimal technology mix.

Key focus end use areas of the strategy include:

1. **Use of hydrogen in industry:** Decarbonising current hydrogen production and use in industries; transitioning to low-carbon hydrogen as an industrial fuel; stimulating new technologies for fuel substitution in sectors such as construction, mining and quarrying equipment; incentivising new technologies for fuel transition in cement, oil refining, glass and lime industries through specialised funds, etc.
2. **Use of hydrogen in power:** Flexible hydrogen-fired power generation ("gas to power") with a focus on turbines; system flexibility through electrolysis and storage ("power to gas", "power to gas to power"). Activities include assessing options for a lasting power market framework and establishing Decarbonisation Readiness requirements for new combustion power plants.
3. **Use of hydrogen for heat in buildings:** Despite uncertainties and scepticism of some stakeholders in the United Kingdom, hydrogen is considered in the strategy as a key option for decarbonising the heat supply of buildings, alongside electrification and heat networks. The strategy adopts a flexible approach, considering diverse heat energy demand in various building types and geographic regions. It emphasises the need for additional data on costs, benefits, safety, feasibility, air quality impact and consumer perceptions of using low-carbon hydrogen for heating. Ongoing efforts encompass studying hydrogen distribution in gas networks, supporting the development and demonstration of hydrogen-ready appliances, and accrediting engineers working with hydrogen. Industrial efforts include conducting first-of-a-kind hydrogen heating trials, with a strategic decision on the role of hydrogen heating expected in 2026.
4. **Use of hydrogen in transport:** Hydrogen can play a pivotal role in decarbonising the largest emission sector, transport, which contributed 27% of UK emissions in 2019. The strategy emphasises the uncertain long-term role of hydrogen in transport but identifies its effectiveness in areas with specific energy density requirements, duty cycles and refuelling times. Key activities include launching the National Bus Strategy with the "green bus revolution", trials of a fleet of up to 370 hydrogen-powered trucks, demonstrating clean maritime transport, supporting the establishment of the first production facilities for sustainable aviation fuel, and modifying the Renewable Transport Fuel Obligation to include use of renewable fuels of non-biological origin (RFNBOs).
5. **Hydrogen blending into the natural gas grid:** In the United Kingdom, 85% of households use gas, and there are historical instances of "town gas" containing around 50% hydrogen. In December 2023, the government decided to support blending up to 20% hydrogen into gas distribution networks under specific strategic conditions. Ongoing trials are under way to assess the safety of hydrogen blending in these networks. After completing the safety assessment, the government will determine whether to proceed with blending based on feasibility and economic considerations (UK Government, 2023).

Box 9 Example of the “champagne” view: the Austrian strategy’s focus on three priorities

The Austrian hydrogen strategy emphasises that hydrogen should be considered in the systemic context of alternative decarbonisation strategies from the perspective of optimising energy use. Under this approach, hydrogen should be used primarily in areas with a high demand for thermal energy or where electrification options are limited. The strategy prioritises the following end use applications:

- High-temperature industrial processes.
- Specific sectors of the mobility industry, such as aviation and maritime transport, which go beyond the expected economic and technical feasibility of direct electrification and transport batteries. In the medium term, an additional pathway emerges here, involving the use of e-fuels and synthetic methane.
- Non-energy uses of hydrogen – for example, as a chemical raw material or reducing agent in reactions – to support the transition from fossil fuel-based value chains.

For this reason, light-duty vehicles and low-temperature heat in homes are not considered as potential end uses of hydrogen.

6. Where?
Export considerations

The resources required to produce green hydrogen are more evenly distributed across the world than fossil fuels. Many countries with the potential to produce large quantities of green hydrogen are posing themselves as energy exporters, as their current energy consumption does not match their theoretical hydrogen production potential. At the same time, current oil and gas producers with good renewable energy resources are willing to export both blue and green hydrogen and maintain their role as energy exporters.

However, there are significant challenges in realising this vision. One major hurdle is the high cost and energy loss associated with transporting hydrogen over long distances. This issue makes it currently not very feasible to transport hydrogen across vast distances at large scale, suggesting that for the near future hydrogen production will be more localised, tailored to the renewable energy capacities of specific regions.

Currently, there is no established international trade in hydrogen, which underscores the enormity of the task ahead. Developing this sector will require overcoming myriad challenges, including technological advancements, cost reduction, organisational restructuring and navigation of complex geopolitical landscapes.

6.1 Positioning

As nations draft and revise their hydrogen strategies, they are not only considering their current energy status but also envisioning their future in the global hydrogen trade, whether as importers, exporters, hubs or independent entities (Figure 15). This shift represents a significant departure from traditional energy dynamics dominated by fossil fuels, with hydrogen emerging as a key player in the quest for a sustainable and secure energy future. The boundaries between these roles are not necessarily rigid; for example, hydrogen (or ammonia) export projects may be developed in countries not primarily focused on exports. However, understanding these roles can provide better insights into strategic perspectives.

Figure 15 Geopolitical positioning of countries

Importer	Exporter	Hub	Self-reliant
European Union Germany Japan Luxembourg Republic of Korea Singapore Spain	Argentina Australia Canada Chile Denmark Ireland Malaysia Morocco Namibia New Zealand Norway Oman Portugal South Africa Trinidad and Tobago United Arab Emirates United Kingdom Uruguay	Belgium Colombia Croatia Italy Netherlands Panama	China Indonesia United States

Self-reliants

Countries with advanced industrial and transport sectors, large resources for hydrogen production, and ambitious decarbonisation targets can pursue self-sufficient hydrogen strategies, enjoying not being dependent on hydrogen imports and focusing on developing domestic supply and demand. Energy and supply chain security considerations serve as important drivers here. The hydrogen strategies of China and the United States are taking this approach. In the United States, hydrogen export is considered in the strategy only in long-term perspective (after 2030), also to provide energy security for US allies. China, as the world's largest producer and consumer of grey hydrogen and a country heavily reliant on oil imports, discusses in its hydrogen strategy a strategic goal of strengthening clean energy supplies by employing hydrogen, creating diverse ecosystems for consuming such energy, and enhancing China's energy security. The strategy does not mention hydrogen exports or imports at all.

Hubs

Countries that have stragetic advantages owing to their geographic location – such as Belgium, Italy, the Netherlands and Panama – are positioning themselves as hubs in the hydrogen sector. They plan to import hydrogen and then export it to countries with higher demand. This strategy involves repurposing existing seaports and gas infrastructure to facilitate the hydrogen trade. These countries aim to have a role as "energy bridges". For example, the federal government of Belgium positions the country as a hub for the import and transit of renewable molecules in western Europe, a goal similarly embraced by the hydrogen strategy of the Netherlands. Belgium's hydrogen strategy mentions that around 50% of the imported hydrogen will transit to other European countries.

Importers

Countries such as Germany, Japan and the Republic of Korea are preparing for a future as hydrogen importers. These countries face challenges such as high industrial demand for hydrogen and limited resources for its production, such as scarce land for renewable energy projects. Currently reliant on fossil fuel imports, these countries are keen to avoid replicating fossil fuel market dynamics and risks, such as oligopolistic structures. Their hydrogen import strategies are heavily influenced by energy security concerns, especially in light of vulnerabilities exposed by conflicts such as the war in Ukraine and COVID-19 supply chain disruptions. These countries aim to diversify their hydrogen sources to mitigate risks related to reliance on a single supplier.

Exporters

Countries with abundant fossil fuel and renewable resources for hydrogen production and relatively low hydrogen demand are considering becoming hydrogen exporters. Fossil fuel exporters, such as Australia, Canada, Norway, and the United Arab Emirates, are transitioning towards hydrogen as a strategic response to the anticipated decline in fossil fuel demand. These nations, with their extensive experience in the energy sector and established infrastructure, are well positioned to shift towards hydrogen exports. For instance, Colombia's hydrogen strategy envisions export potential in hydrogen comparable in revenue to the current coal export (more than USD 5 billion) in the long term. However, this transition presents challenges, such as balancing the need for global sustainability against replicating past economic and power structures under a different guise.

Additionally, potential future renewable energy powerhouses such as Morocco and Namibia see hydrogen as an opportunity to export renewable energy resources. This transition, while promising, requires careful consideration to avoid scenarios where green hydrogen plans divert financial and political capital from the decarbonisation of local energy uses or opportunities for enhanced energy access. Green hydrogen production in developing countries can provide notable structural benefits (UNIDO, IRENA and IDOS, 2023).

6.2 Strategic considerations for hydrogen trade

The hydrogen trade market will be substantially different from the fossil fuel market. A key aspect is the move from an oligopoly structure to an oligopsony one, where a limited number of importers will interact with a relatively larger group of exporters. This dynamic will move considerable negotiation power to buyers, allowing them to dictate aspects such as the quality standards of hydrogen, with a particular emphasis on certification and origin.

Understanding this evolving market is crucial for policy makers as they position their countries as either exporters or importers of hydrogen. Comprehending these dynamics is vital to making well-informed decisions that align with their country's economic, environmental and strategic interests.

Diplomacy and regionalisation of hydrogen trade

Trade and investment relationships are inherently linked with broader political considerations. Any changes in economic relations can have a profound impact on political ties, and vice versa. As such, the emergence of markets in green hydrogen and products could bring about a significant shift in political alliances and relations between countries.

The current trade relations in oil and gas markets are largely shaped by geology, as hydrocarbon reserves are concentrated in a limited number of countries. Meanwhile, around 80% of the world's population lives in countries that are net importers of fossil fuels.

By contrast, renewable resources such as solar, wind and hydropower are available in every country, although the strength and quality of these resources vary across the globe. For this reason, it is very unlikely that a green hydrogen cartel will emerge similar to historical fossil fuel alliances. The pre-conditions for an effective cartel are that a relatively small number of producers control a substantial share of the market, and that they must be able to set and enforce production quotas, control capacity expansion and limit the entry of new producers. None of these pre-conditions are likely to be met in the case of green hydrogen.

Potentially, the establishment of a global Hydrogen Alliance – a collaborative trade consortium involving potential key importers and exporters – may become a pertinent consideration over time (Pepe *et al.*, 2023). Energy relations are likely to be regionalised, transforming the geopolitical map.

This market structure suggests that hydrogen trade will be more diverse compared to the existing oil and gas markets, with a dual form: a regional market facilitated by pipelines and a global market focused on ammonia, methanol and other liquid fuels (IRENA, 2022c, 2022e). This means that for countries distant from large demand centres, their market will be limited to green hydrogen derivatives and potentially semi-finished energy-intensive industrial products.

Germany and Japan are among the trailblazers in forging new hydrogen trade relations, with Germany emerging as the clear leader in this direction from 2021 to 2023. As of mid-2024, Germany was in the process of drafting a hydrogen import strategy. This strategy will include specific measures aimed at encouraging imports from European countries in the short term and from non-European countries in the medium and long terms. Additionally, Germany has established hydrogen diplomacy offices in Angola, Kazakhstan, Namibia, Nigeria, Oman and Saudi Arabia between 2022 and 2023, with plans to open an office in Ukraine. Germany has also entered into numerous hydrogen memorandums of understanding with countries and organisations. Germany actively funds hydrogen research and facilitates the development of hydrogen strategies. Notably, it supported the H2Global mechanism, for international hydrogen auctions.

Japan is engaging with Australia, Brunei, Norway, Saudi Arabia and others on setting up value chains for the hydrogen trade. These initiatives are not just about securing energy resources, but also about fostering technological collaboration, economic development and environmental sustainability. Hydrogen diplomacy thus extends beyond mere trade, encompassing broader aspects of international co-operation.

Certification and regulation considerations

Importing nations hold considerable sway in shaping hydrogen certification standards, a crucial factor in the hydrogen trade. Countries willing to import green hydrogen over any other colour want to ensure that the hydrogen they import meets their environmental standards and contributes to enhancing energy security (Box 10). In the case of future imports into the EU, this involves effectively distinguishing truly green hydrogen from less sustainable variants such as grey hydrogen. This vigilance is key to maintaining the integrity of the local green hydrogen market and avoiding the risk of inadvertently supporting environmentally detrimental practices.

However, importers must navigate a delicate balance. Setting overly stringent requirements could potentially alienate suppliers who might then turn to markets with more relaxed certification standards. A critical decision for importing countries is the establishment of limits for the carbon intensity of imported green hydrogen and the methods for its measurement. The criteria they set can greatly impact the global playing field, affecting the competitive edge of both exporting countries and their hydrogen producers.

The influence of importers extends beyond mere certification. They play a pivotal role in setting broader rules and regulations that govern the trade of green hydrogen. These countries view green hydrogen as a cornerstone for industrial and economic growth, leveraging their market power to steer the development and application of hydrogen technologies. This influence is a powerful tool in shaping the future trajectory of the hydrogen industry. In doing so, importers actively mould the market by playing a key role in the sustainability and viability of the green hydrogen sector.

Box 10 Germany: certification of imported hydrogen with additional sustainability requirements

The German hydrogen strategy was first unveiled in the summer of 2020, and three years later an updated version was published. This revised strategy places a significant emphasis on hydrogen imports, accompanied by a detailed delineation of approaches to hydrogen certification. The strategy envisions that around 50-70% (45-90 TWh) of Germany's hydrogen demand will be met through imports of hydrogen and its derivatives from other countries. The share of imports in fulfilling hydrogen demand is anticipated to continue to rise post-2030. The updated hydrogen strategy mentions the intention to introduce a dedicated strategy focused on hydrogen imports (under development at the time of writing). The goal is to facilitate international imports from a diverse array of exporting nations that adhere to minimum standards and, if feasible, are governed by a shared or recognised hydrogen certification system.

The strategic vision aims to champion "the utilisation of green hydrogen and, when necessary, during the market ramp-up phase, low-carbon blue, turquoise, and orange* hydrogen to a limited extent on the application side." This involves considering ambitious limits on greenhouse gas emissions, encompassing upstream emissions along the value chain. Under the strategy, this hydrogen must conform to the EU's greenhouse gas emission limits based on a life-cycle analysis aligned with savings relative to fossil fuels (3.4 kilograms CO_2 equivalent per kilogram hydrogen [kg CO_2-eq / kg H_2]).

The strategy underscores that hydrogen export projects in partner countries receiving support from Germany should align with the United Nations (UN) Sustainable Development Goals. Additionally, they must adhere to international human rights standards, labour and environmental norms, and corporate due diligence standards (*e.g.* OECD Guidelines for Multinational Enterprises, UN Guiding Principles on Business and Human Rights, and the 2030 Agenda).

** Orange hydrogen is hydrogen from waste and residues.*

None of the current hydrogen certification systems are adequate for international trade. Moreover, there are deficiencies in standards and in the design of eco-labelling and certification, leading to insufficient information on certificates to enable equitable comparisons across borders (IRENA and WTO, 2023). Significant regulatory advancements were made in hydrogen certification in the last two years. The United Kingdom introduced the Low-Carbon Hydrogen Standard to determine eligibility for support schemes and is consulting on a certification scheme. The European Commission issued two Delegated Acts, one defining conditions for hydrogen as renewable fuels of non-biological origin (RFNBOs) and another for assessing greenhouse gas emission savings from RFNBOs. The US Department of Energy proposed a clean hydrogen production standard, setting an initial life-cycle emissions target of no more than 4 kg CO_2 eq/kg H_2, with further methodological details pending.

These varied approaches in certification criteria and methodologies by different countries indicate a need for greater international coordination. Without it, certification differences may become a trade barrier, limiting suppliers to specific off-takers and restricting trade to bilateral agreements. During COP 28, more than 30 countries, constituting around 80% of the potential global market in hydrogen, signed a declaration of intent. This declaration emphasises the mutual recognition of certification schemes for renewable and low-carbon hydrogen and derivatives, following the suggestions of IRENA, IEA and UN High-level champions in the *Breakthrough Agenda Report 2023* (IEA, IRENA, and UN-CCHLC, 2023). At COP 28, the International Organization for Standardization (ISO) introduced a new technical specification (ISO/TS 19870) aimed at providing a framework for harmonising, ensuring safety, inter-operability and sustainability throughout the hydrogen value chain.

At the end of 2022, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) initiated a certification mechanisms task force, aiming to assess the conditions for inter-operability of low-carbon and renewable hydrogen certification mechanisms and to identify common information requirements to enable low-carbon and renewable hydrogen certification equivalency 2023 (IEA *et al.*, 2023).

Export as an important chokepoint

Reliance on hydrogen exports in a hydrogen strategy can be a critical chokepoint (see section 9.2). If exports do not materialise as planned, or if infrastructure is not made available for exports, this can halt the progression of the hydrogen strategy. This situation arises because the absence of expected revenues and subsequent investments disrupts the intended economic flow.

The reliance on exogenous import targets introduces a risk of overshadowing alternative opportunities. By focusing primarily on meeting specific external demands, countries may neglect the exploration of domestic or regional markets, as well as potential avenues for technological innovation and value creation within their own borders. In the export-oriented strategies, the export focus is justified by three main sources of information:

- The demand from developed countries. Import targets such as those in Germany and Japan are explicitly mentioned in the strategies (*e.g.* Morocco).
- Market analyses by respected international organisations, such as IRENA and the IEA. Reports assessing the future market of hydrogen, such as *Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward*, are explicitly mentioned (*e.g.* Trinidad and Tobago).
- Lastly, strategies may have their own in-house projections of expected export markets or rely on third parties.

While numerous developing countries are adopting export-focused hydrogen strategies, underpinned by various memorandums of understanding, the expected surge in the global hydrogen market is not a certainty. Changing geopolitical situations, regulatory ambiguities and new competing technologies could profoundly affect the real demand and growth of hydrogen exports. Moreover, the existing forecasts for hydrogen import potential often follow a conventional narrative, typically reflecting the existing global dynamics (industries in the Global North, resources from the Global South).

Adopting a versatile and adaptive approach – one that considers a range of possibilities and is open to adjustments in response to changing market dynamics – is key for developing countries. This strategy will enable these countries to better manage uncertainties and exploit potential opportunities that might not fit within the conventional narrative. The reliance on exports should be complemented with efforts to foster domestic demand and infrastructure development. Ensuring a more resilient and sustainable hydrogen sector, and continuously monitoring global market trends, helps in adapting strategies to the evolving landscape, ensuring that the hydrogen sector remains robust and adaptable to change.

The concept of offtake risk is central to this discourse. Countries focusing on hydrogen export must secure guaranteed buyers or establish an "anchor demand" to mitigate risks associated with export reliance. This anchor demand not only offers security to local investors but also ensures the creation of a hydrogen sector within the country that is less dependent on international market dynamics.

Carbon leakage resistance

The term "carbon leakage" refers to a situation where companies move their facilities to jurisdictions with weaker emission constraints, resulting in an increase in global emissions. This may occur due to higher costs incurred by companies to comply with climate policies, such as explicit carbon pricing or mandates targeting industry.

The use of green hydrogen may also face this issue if businesses choose to relocate to areas where its use is not necessary, resulting in decreased global demand. Carbon leakage raises both environmental and socio-economic concerns, putting global decarbonisation efforts at risk. To combat carbon leakage, policies are being implemented to avoid or minimise the risk.[7]

Border carbon adjustments (BCAs) are carbon-based import taxes that account for the difference in carbon pricing policies between countries, making polluters pay the same carbon price as local industry. BCAs are instrumental in mitigating carbon leakage, a phenomenon where production shifts to regions with less stringent carbon emission regulations. This shift undermines the environmental policies of countries that have stricter carbon controls. BCAs address this by imposing a levy on imported goods equivalent to the domestic carbon price, ensuring that foreign producers face similar costs for carbon emissions as domestic ones. This equalisation discourages the relocation of industries to countries with lax environmental standards, thereby preserving the integrity of a country's climate policies and global environmental efforts. By doing so, BCAs effectively maintain the intended environmental benefits of national carbon policies without sacrificing economic competitiveness. The most prominent example of such policies is the EU's Carbon Border Adjustment Mechanism.

One of the key benefits expected by BCAs is the promotion of fair competition between domestic industries and their international counterparts. In countries where stringent carbon emission regulations are in place, domestic producers face higher costs, potentially putting them at a competitive disadvantage compared to foreign producers from regions with looser environmental regulations. BCAs level this playing field by ensuring that the carbon costs are similar for both domestic and foreign producers.

7 Policies to halt carbon leakage are a way to balance the asymmetric climate policies of different countries. To effectively address carbon leakage, countries could adopt a multilateral strategy and reach agreement on the risks of climate change. The disparity in policies and objectives will only grow if there is no international consensus on the effects of rising emissions. This is what creates the foundation for carbon leakage. Harmonised international climate regulations will make it easier to manage carbon leakage and reduce global emissions, increasing the need for global decarbonisation solutions.

BCAs may serve as a catalyst for broader adoption of carbon pricing mechanisms globally. By imposing costs on imports from countries without equivalent carbon pricing, BCAs create an economic incentive for these countries to adopt similar measures. This indirect influence can lead to a domino effect, encouraging more countries to implement carbon pricing, thus expanding the global effort to control carbon emissions.

For exporting industries in countries with less stringent or no carbon pricing, BCAs present a direct financial challenge, as the products of these countries become less competitive in markets with BCAs. To avoid the additional costs imposed by BCAs and remain competitive, exporting industries are incentivised to decarbonise. The push for decarbonisation may lead governments in exporting countries to reassess and potentially reform their regulations that may hinder individual companies' decarbonisation actions (*e.g.* allowing power purchase agreements where now forbidden).

As industries seek to decarbonise, they become credible off-takers for renewable energy producers. The increased demand for renewable energy, driven by industries' need to decarbonise, leads to more renewable energy projects being developed. As more projects are undertaken, developers and other stakeholders in the renewable energy sector gain valuable experience and expertise. This encompasses technical know-how, understanding of local regulatory environments, and efficient project management practices applied to the local context. As renewable energy developers gain experience and establish a track record of successful projects, and as governments and users get acquainted with these projects, this can reduce perceived country risk. Experienced developers are better equipped to navigate local challenges, increasing investor confidence.

However, BCAs can greatly impact global trade and economic dynamics. While they aim to reduce carbon leakage and promote fair competition, BCAs might also lead to reduced global demand for certain goods, impacting the terms of trade, especially for countries exporting energy-intensive products. This can have a ripple effect on the global economy, necessitating careful consideration and design of BCAs to balance environmental goals with economic realities. Additionally, the implementation of BCAs can lead to complexities in international trade relations, particularly if perceived as a unilateral trade barrier or a protectionist measure.

Implementing BCAs also involves significant administrative and compliance challenges. Companies must accurately report their carbon emissions, and this process can be complex, requiring robust systems for monitoring, reporting and verifying emissions. These requirements add administrative and financial burdens to businesses, particularly for small and medium-sized enterprises, which might lack the resources for such compliance.

International collaboration is essential in implementing BCAs. Harmonising carbon pricing policies and standards across countries can reduce the risk of trade disputes and economic inefficiencies. Co-operation can also facilitate the sharing of best practices, reduce administrative burdens and ensure that carbon pricing policies are effectively integrated into the global trading system. This collaboration is particularly important for supporting developing countries, which may face greater challenges in adapting to carbon pricing and BCA regimes.

For this reason, the design of BCAs should involve critical considerations, such as the fair burden-sharing in carbon pricing. The principle of common but differentiated responsibilities (CBDR), established under the Paris Agreement, acknowledges that all governments are responsible for addressing climate change, but not equally, reflecting the historical contributions to environmental degradation and differences in economic capacities for climate mitigation and adaptation efforts.

Fair burden sharing implies providing support to developing countries, in the form of technology transfer, financial assistance or capacity building to help them transition to low-carbon economies without suffering disproportionate economic setbacks. The revenue generated from BCAs can be used to support climate action, both domestically and internationally. Fair burden sharing could involve using a portion of these funds to aid climate adaptation and mitigation efforts in developing countries, helping to address the global nature of the climate crisis (WTO, 2022).

The other pathways: green hydrogen as a pull

The physical properties of coal, being bulky and heavy, made it inefficient and costly to transport. Consequently, it was more practical to produce steel near coal deposits and then transport the steel, rather than moving coal to steel production sites (McWilliams and Zachmann, 2021).

Hydrogen is light, fugitive and costly to transport. It may therefore be more efficient to produce steel, basic chemicals and e-fuels at the site of hydrogen production, and then transport the products, than to transport hydrogen to industrial centres.

For centuries, access to energy has been a major factor determining the location of industrial activity. The phenomenon of the "death of distance" – a marked decrease in freight transport costs allowing industrial locations to be less dependent on natural resource proximity – is a relatively newer development. However, this concept does not fully apply to hydrogen (IRENA, 2022c). Transporting renewable energy, whether as electricity or hydrogen, still incurs relatively high costs. The most cost-effective method of energy transport remains through materials and products.

The global energy transition will change the sources of energy capture, conversion and distribution globally. In a net zero future, therefore, access to cost-competitive energy will be determined largely by renewable sources of electricity and fuels derived from this input. Three elements can drive this phenomenon, namely:

1. the willingness of industrial agglomerates to relocate or open new facilities
2. the cost of transporting energy, and
3. the difference in cost of renewable energy (McWilliams and Zachmann, 2021).

While it is true that the location of industrial production is influenced by a multitude of factors – including human capital, infrastructure, labour costs, industrial policy, country risk and corruption levels – the cost of energy is increasingly pivotal, especially for energy-intensive and hard-to-abate industries where energy and fossil fuel feedstock costs constitute a large portion of total production expenses. As global efforts intensify towards achieving net zero economies, and with initiatives such as the EU Carbon Border Adjustment Mechanism, industries that traditionally depend heavily on fossil fuels are compelled to seek access to more affordable and clean energy sources to stay competitive.

A critical factor driving the relocation is the "renewables pull" effect, which encapsulates the growing allure of renewable energy-rich regions for energy-intensive industries. This trend is particularly evident in sectors such as steel and chemicals, where it is often more cost effective to transport intermediate and finished products, such as direct reduced iron (DRI), ammonia, and ethylene, rather than the hydrogen used in their production. This creates mutual benefits: regions abundant in renewables can boost local employment and economic value by exporting green intermediates, while those lacking in renewables can import these intermediates, thus maintaining their competitive edge in the final stages of product manufacturing.

A notable example is the establishment of the first commercial-scale steel factory using green hydrogen in northern Sweden, an area endowed with low electricity costs and plentiful iron ore. This development symbolises the larger trend of renewable energy, especially green hydrogen, becoming a key determinant in industrial location decisions amid the global energy transition.

Importantly, the establishment of new production facilities in renewable-rich countries does not necessarily lead to the closure of existing plants. Rather, the energy transition presents opportunities for growth across various industries. The anticipated increase in global population and the corresponding rise in infrastructure requirements signal a growing demand for products such as ammonia and steel. Transporting these green products will be more economical than shipping green hydrogen itself. Therefore, countries with abundant renewable energy resources are well positioned to set up new industrial facilities, exporting semi-finished or finished products and capitalising on the differential in energy costs.

This consideration could affect the global hydrogen and derivatives trade projections. To do so, models would need to change prospected roles of Global South countries, identifying new demand centres where energy is cheap but difficult to transport.

Effective energy sector policies are crucial in this transition. They play a vital role in minimising the political, regulatory and financial uncertainties faced by renewable energy developers, thereby facilitating the decarbonisation of local energy sectors and promoting green industrialisation. National strategies should prioritise enhancing green hydrogen production, improving transport and storage infrastructure, and encouraging international collaboration. This approach aligns with broader low-carbon development objectives, fostering domestic demand for green hydrogen and laying the groundwork for future export-oriented initiatives.

For fossil fuel exporting countries, the optimal response to the challenges posed by the energy transition lies not solely in hydrogen exports but in restructuring their economies towards a low-carbon model, with hydrogen playing a significant role. This involves integrating hydrogen strategies with comprehensive low-carbon development and green industrial transformation plans, which include energy storage and infrastructure strategies. Such integrated approaches not only create long-term, sustainable local demand for hydrogen but also establish a foundation for export-oriented project implementation.

The hydrogen strategy of the United Arab Emirates, unveiled in August 2023, exemplifies this approach (Box 11). While positioning the country as a future hydrogen exporter, the strategy emphasises decarbonising local industries and diversifying the economy using local resources, showcasing a balanced view of both domestic and export potentials of hydrogen. This strategic direction underscores the multifaceted role of hydrogen in both local and global contexts, marking a significant step in the global energy transition.

Box 11 The United Arab Emirates: energy-exporting country with a focus on deployment of local demand for low-carbon hydrogen

The United Arab Emirates possesses 5.6% of the world's total proved crude oil reserves and accounts for 8.1% of global crude oil exports. It holds the seventh largest natural gas reserves globally, and oil outputs contribute around 30% of the country's gross domestic product (GDP).

In 2023, the UAE approved a hydrogen strategy, with a primary focus not on hydrogen export but on production. The goal is for the country to become a leading global producer of low-carbon hydrogen by 2031, leveraging the potential of renewable energy sources, natural gas reserves, and carbon capture, utilisation and storage (CCUS) capabilities. Notably, the strategy emphasises developing domestic hydrogen consumption in rapidly advancing UAE sectors such as shipping, aviation, aluminium production, and iron and steel.

The strategy underscores that, under favourable market conditions, the sector demand (2.1 Mt by 2031) could surpass projected production capacities (1.4 Mt). Hydrogen and its derivatives are considered an additional opportunity, leveraging the UAE's advantageous geographic location between the European and Asian markets and its well-developed port infrastructure.

The strategy highlights that a substantial domestic demand for low-carbon hydrogen will position the UAE to outpace competitors in project developments, as it does not rely on demand in other countries. The hydrogen strategy aligns with scenarios for further economic diversification within the UAE's National 2050 Net Zero strategy.

7. How much?
Target setting

Once the priorities are established, setting precise and informed targets is a key endeavour, which must consider the distinct objectives and conditions of each jurisdiction. Targets are often the most-cited design elements of a strategy and can be seen as the potential market by investors.

The main function of targets is to signal the country's long-term political commitment to green hydrogen, which is required to attract the investment needed to develop the sector. The more detailed, specific, and credible the target is, the more likely it is to drive deployment, including through increased market confidence (IRENA, 2022h).

To make a target credible, the main drivers (see section 2) behind the strategy for hydrogen deployment in the country need to be put centre stage during target setting.

7.1 Target-setting considerations

Before defining targets, it is essential to consider the current renewable energy potential and future, the current and future demand for hydrogen, existing infrastructure, and the technical and economic feasibility of hydrogen technologies within a country. In addition, considering a broad range of options and aligning them with overarching policy goals and existing capabilities is crucial.

- **Renewable energy potential and future.** Setting green hydrogen targets requires clarity on the renewable energy potential of various technologies. This is conducted through resource assessments and suitability analyses for specific technologies (see Box 3.3 in IRENA, 2022h). In addition, the future demand for renewable energy needs to be considered, as green hydrogen production adds electricity demand, comparable to or even multiple times the installed capacity of a country's existing power system. Additional renewable energy targets dedicated to hydrogen would enhance credibility (Box 12).

Box 12 Renewable energy targets in hydrogen strategies

Integrating renewable energy targets specifically for green hydrogen production within national hydrogen strategies is instrumental for several reasons. Setting dedicated renewable energy targets for green hydrogen not only enhances the credibility of hydrogen strategies but also ensures the alignment of hydrogen production with sustainability and decarbonisation objectives. As the demand for hydrogen is projected to increase, establishing clear targets for renewable energy use in hydrogen production addresses the additional demand on power systems, ensuring that this demand is met sustainably.

In essence, incorporating renewable energy targets in green hydrogen strategies facilitates a structured and sustainable approach to hydrogen production, ensuring that it contributes effectively to decarbonisation efforts while addressing the increasing global energy demand.

At least 15 countries have undertaken this exercise in their hydrogen strategies: Algeria, Argentina, Australia, Colombia, Ecuador, India, Ireland, Kenya, New Zealand, Oman, Sri Lanka, Trinidad and Tobago, the United Arab Emirates, the United Kingdom and Uruguay.

- **Current and future demand for hydrogen.** Targets need to consider the overall hydrogen demand, its forecast and any changing patterns in all sectors of the economy. In this, the use of LTES and stakeholder engagement are crucial (see sections 3 and 4). The different end uses selected as priorities need to be considered in conjunction, with careful consideration of how they can interact. For example, large demand centres or hydrogen valleys could be big enough to enable economies of scale, making the shift to green hydrogen even more cost effective in these applications compared to distributed applications, avoiding high infrastructure costs at the onset and making green hydrogen cheaper for distributed uses in the future.
- **Existing and future infrastructure.** It is important to consider green hydrogen integration with other energy transition technologies and infrastructures. This approach ensures that the deployment of green hydrogen technologies is not only ambitious but also practical, tailored to the specific context of each jurisdiction. Grid system operators' expansion plans can inform about future opportunities or chokepoints.
- **Technical and economic feasibility.** Many of the components in the green hydrogen value chain have already been deployed on a small scale and are ready for commercialisation, now requiring investment to scale up. At the same time, some technologies have not yet been demonstrated at scale (such as ammonia-fuelled ships), and scaling up green hydrogen could make those pathways more attractive as production costs decrease. However, it is important to maintain a realistic outlook for technologies that have still to be deployed at the scale expected (*e.g.* gigawatt-scale electrolysers, or gigafactories), and consider various learning curves when setting up the targets.
- **Achievability.** In the end, the targets need to be implementable and achievable within the determined time frame. This means considering the potential future boundaries. The current and future level of development of the green hydrogen value chain and needed infrastructure play a key role, but the strategies should take into consideration other potential barriers (see section 8), such as the available human capital and the availability of relevant services (supply chain, construction, maintenance, etc.) and resources. If targets exceed current capacities, dedicated policies will be needed (section 9).

It is important to acknowledge the inherent uncertainties involved. Developing flexible strategies that can adapt to changing circumstances, and incorporating robust scenario planning, are essential for navigating these uncertainties effectively and designing targets that are achievable.

7.2 Target design elements

Target setting can be achieved considering various design elements. This section presents the main design elements from current strategies. Each design element includes a choice from the strategy makers, with various trade-offs. Strategy makers must decide between capacity and output targets, share versus absolute values, long and short term, supply and demand, coverage and technology specificity.

Capacity versus quantity targets

When designing targets for green hydrogen production, a decision involves whether to establish these targets based on capacity (*e.g.* MW of electrolysers) or output (*e.g.* megatonnes of hydrogen or derivatives produced), or to use a blend of both (Box 13). Targets aimed at expected hydrogen demand are typically expressed in energy units (Mt or TWh per annum) or as a percentage of final energy consumption.

- **Capacity-based targets** offer simplicity in monitoring and tracking and make it easier for policy makers to create incentives for technology deployment. Capacity-based targets can also provide a larger confidence to developers, as the targets do not include operational and demand-side constraints.
- **Quantity-based targets,** on the other hand, emphasise the actual production of green hydrogen, usually measured in Mt. This focus on production over capacity can provide a more accurate reflection of hydrogen's contribution to energy systems, as it accounts for operational efficiency and capacity factors of hydrogen production facilities, and addresses the future demand side of hydrogen. Output-based targets can set up policies that encourage the efficient operation of electrolysers, potentially contributing to a reduction in the levelised cost of hydrogen and promoting the integration of green hydrogen into the energy mix based on actual production and demand figures.
- Some jurisdictions have opted for **combining capacity and quantity targets**, leveraging the strengths of both approaches. This involves setting clear capacity goals for electrolyser installations alongside expected output targets for green hydrogen production, often assuming time-evolving capacity factors to link the two. This approach supports the deployment of electrolysers while also emphasising the importance of the actual hydrogen produced as a key indicator of success.

Box 13 Examples of capacity-based and quantity-based targets

Kenya's hydrogen strategy outlines objectives for electrolyser capacity, aiming for 0.1 GW by 2027 and 0.25 GW by 2032, alongside targets for renewable energy capacity allocated for hydrogen production, set at 0.15 GW and 0.45 GW respectively.

Similarly, Türkiye's hydrogen strategy sets goals for electrolyser capacity, aiming for 2 GW by 2030, 5 GW by 2035 and 70 GW by 2053. These targets are accompanied by cost reduction objectives, aiming to lower the production cost of green hydrogen to below USD 2.4/kg by 2035 and below USD1.2/kg by 2053.

The United Kingdom has set a target for the capacity of green and blue hydrogen production, aiming for 10 GW by 2030, with at least 50% dedicated to green hydrogen.

In contrast, Namibia's hydrogen strategy focuses on targets for green hydrogen production quantities, aiming for 1-2 Mt by 2030, 5-7 Mt by 2040, and 10-15 Mt by 2050. Canada has set targets for hydrogen consumption quantities, without a focus on the source of its production, aiming for 3 Mt by 2025, 4 Mt by 2030, and 20 Mt by 2050.

The United Arab Emirates, aiming to become the leading global producer of clean hydrogen by 2031, has established targets both in production quantities (1.4 Mt by 2031, 7.5 Mt by 2040, and 14.9 Mt by 2050) and in electrolyser capacity (8.7 GW by 2031, 55.1 GW by 2040, and 83.2 GW by 2050), alongside dedicated renewables (15.3 GW by 2031, 97.3 GW by 2040, and 208.3 GW by 2050).

The updated Japanese hydrogen strategy also adheres to combined objectives, encompassing targets for hydrogen consumption quantities (3 Mt by 2030, 12 Mt by 2040, and 20 Mt by 2050), as well as a target for electrolyser capacity of 15 GW by 2030 "in combined domestic and international markets for Japanese-related companies (including parts and materials manufacturers)".

Shares versus absolute values

When setting targets for green hydrogen production or consumption, the strategy can determine them either as a share of the energy, gas or hydrogen mix (relative to a baseline) or as a fixed absolute amount.

- **Share targets** emphasise the role of green hydrogen within the broader energy landscape, illustrating the commitment to climate goals by potentially displacing fossil fuels. For example, setting a target for green hydrogen to constitute a certain percentage of the total hydrogen consumption by 2030 (or just for specific sectors, for example in refining or ammonia production) can signal a clear ambition towards decarbonisation, where hydrogen is a part of the solutions to decarbonise the current mix and not an additional element. However, share targets can introduce challenges related to predictability and measurement. Energy demand forecasting is fraught with uncertainties, making it difficult to establish a reliable baseline for percentage targets. This can result in either overestimation, leading to excess production with limited off-take, or underestimation, which may not fully capitalise on the potential for green hydrogen in energy transition.
- **Absolute value targets**, conversely, provide clear and quantifiable objectives for green hydrogen production, such as setting a goal for producing a specific quantity of green hydrogen by a certain year. This approach simplifies planning, implementation, and monitoring, allowing for direct policy applications through mechanisms such as auctions. These are the most common targets in strategies. Absolute targets offer clarity and certainty for market participants and investors, giving a straightforward indication of the market size and encouraging investment across the supply chain.

Long versus short term

The distinction between short- and long-term goals mirrors the broader strategic planning seen in renewable energy and climate action frameworks, notably with 2030 and 2050 serving as common benchmark years.

- **Short-term targets**, typically aiming for the 2030 horizon, are set to catalyse immediate actions and responses. These targets underscore the urgency of initiating green hydrogen projects, align with current political and policy cycles to secure commitment and funding, and offer a degree of flexibility that allows for adjustments based on early experiences and technological evolution. They serve as a launching pad, setting attainable goals that can stimulate early investments, build initial infrastructure and begin the shift towards more sustainable energy practices. The importance and difficulty of goals for 2030 lie in their need to be specific and sufficiently realistic, well-calibrated to kick-start the deployment of green hydrogen in the country within a short-term horizon.

- **Long-term targets**, often aiming for 2050, should align with sustainability and carbon neutrality ambitions. These targets are essential for signalling a steadfast commitment to the green hydrogen sector, reassuring investors, manufacturers and service providers of the long-term viability and demand for green hydrogen technologies and applications. Such foresight is crucial for guiding significant, capital-intensive investments in production capacity, infrastructure and the development of a skilled workforce across the green hydrogen value chain. It also ensures that the foundation laid in the short term is scalable and can evolve to meet more ambitious future energy and environmental goals.

The presence of both short- and long-term targets in green hydrogen strategy acknowledges the immediate need to kick-start the transition towards green hydrogen while ensuring that these efforts are strategically aligned with the broader, long-term vision of a sustainable, low-carbon energy future.

Supply versus demand

In the context of setting targets for green hydrogen, the distinction between supply-side and demand-side objectives is critical. Supply-side targets focus on the quantities of green hydrogen to be produced, typically measured in millon tonnes, while demand-side targets focus on the consumption of hydrogen (sometimes accompanied by import targets) and can be in absolute or share terms.

- **Supply-side targets** can drive investment in electrolyser capacity and the necessary infrastructure for hydrogen production. They can be more easily used to design support mechanisms such as investment aid, exemptions from electricity taxes, auctions and tariffs (IRENA, 2021a). However, without a corresponding increase in demand, there is a risk that supply-side initiatives may lead to a lack of real demand and offtake risks, underscoring the importance of simultaneous focus on demand creation.
- **Demand-side targets**, on the other hand, aim to foster the integration of green hydrogen in the key sectors. Demand-side targets can support the design of policies such as quotas and Carbon Contracts for Difference (IRENA, 2022i). However, the challenge lies in stimulating enough demand to match the supply in a way to achieve market maturity, especially considering the current concentration of hydrogen demand and the slow penetration in new uses.

Implementing a balanced strategy that encompasses both supply and demand could lead to the successful scale-up of the green hydrogen sector as a way to solve the hydrogen deadlock (see section 7.5).

Coverage (demand-side targets)

Coverage refers to whether the target covers the entire energy sector or specific end uses such as the steelmaking or petrochemical sectors.

- **Targets covering all end uses** inherently require less initial study and research. This broader approach does not necessitate the detailed analysis of sector-specific needs, challenges and potential for green hydrogen integration. Instead, it sets a general framework that leaves the market to decide the most efficient and cost-effective pathways for green hydrogen use. This approach may accelerate its adoption in areas with the most immediate commercial viability.
- Alternatively, **targets on specific end uses**, such as a goal for a certain percentage of green hydrogen in the industrial mix, can support the development of sector-specific policies, driving technological innovation and adoption in areas critically in need of decarbonisation, such as steelmaking and petrochemicals.

Technology specificity (supply-side targets)

In the realm of green hydrogen development, the distinction between technology-neutral versus technology-specific targets refers to the supply-side targets of green hydrogen, and the decision to support a specific electrolysis technology (alkaline, PEM [proton exchange membrane], SOEC [solid oxide electrolyser cell], etc.) or make a distinction between blue and green hydrogen targets.

- **Technology-neutral targets** simplify target setting and policy design, especially in the nascent stages of hydrogen market development. This allows the market to determine the most cost-effective and efficient technology based on existing conditions, technologies and resource availability, and demand patterns.
- **Technology-specific targets** avoid the competition between technologies by assigning targets for each technology. By promoting the simultaneous development of a range of different options through specific targets, policy makers can enable more technologies to emerge and to grow. Adopting technology-specific targets allows for partial achievements (*e.g.* meeting the green hydrogen target alone), and electrolyser-specific targets could accelerate the development and commercialisation of diverse electrolyser technologies, ensuring a broader base of options for green hydrogen production. This approach also could help in the nurturing of national champions.

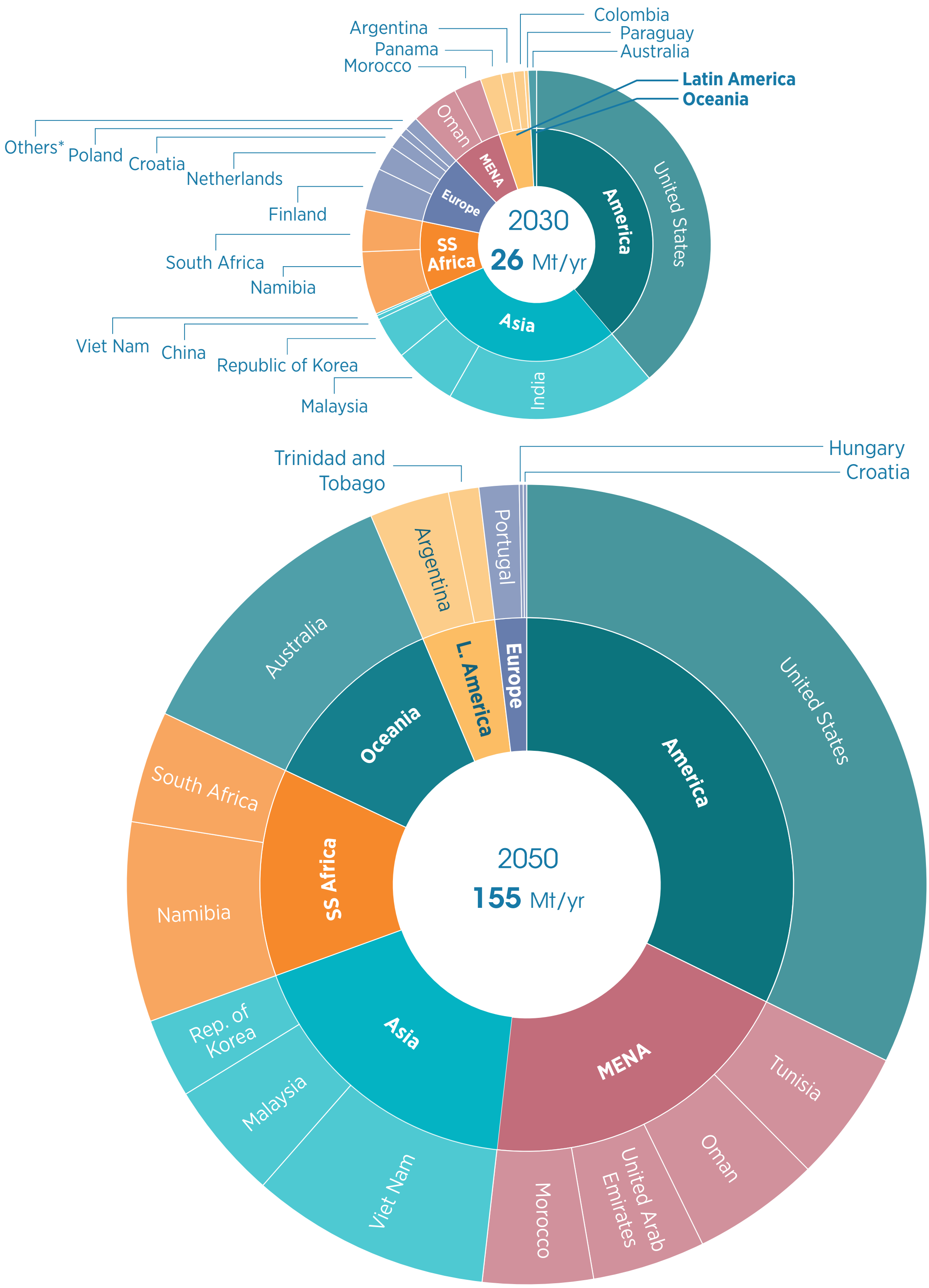
7.3 Current status

Targets are a common feature of hydrogen strategies, and it is possible to identify some common trends.

1. **Absolute value targets are the most common**. The dominance of absolute value targets in green hydrogen strategies signifies a preference for clear, quantifiable objectives that stakeholders can rally around. Such targets provide a straightforward goal for the amount of green hydrogen to be produced or consumed, simplifying planning, implementation and monitoring for all parties involved. This approach fosters a sense of certainty and can more effectively attract investment by offering a concrete indication of the market size and potential growth opportunities in the green hydrogen sector.
2. **Short-term targets are more common than long-term targets**. This highlights the urgency among policy makers to kick-start the green hydrogen sector and achieve early wins in the transition towards a low-carbon energy system. Short-term targets (usually up to 2030) can act as stepping stones, building momentum for green hydrogen deployment and encouraging immediate action and investment. This approach aligns with the need to make significant progress in the near term to meet broader climate goals and energy transition timelines. However, as the 2030 deadline approaches, a redefinition of the targets by 2040 may provide a stable (and attainable) outlook.
3. **Although short-term targets are more common**, the aggregate ambition represented by long-term targets is significantly higher, both in terms of volume and capacity.
4. **Most hydrogen strategies use electrolyser technology-neutrality at this stage**. This neutrality allows for flexibility and market-driven decisions on the best technologies to meet production targets. However, as the green hydrogen sector matures and the distinct roles and advantages of different electrolyser technologies become clearer, there may be a shift towards more technology-specific targets to optimise the production landscape for green hydrogen.
5. **Quantity and capacity targets are equally popular**.

Collectively, countries aim to reach a hydrogen production milestone of 25.7 Mt by 2030, escalating to 135.8 Mt by 2050. While 23 countries have established short-term production goals, a smaller group of 14 countries have set their sights on long-term achievements, with 11 countries planning for both (Figure 16).

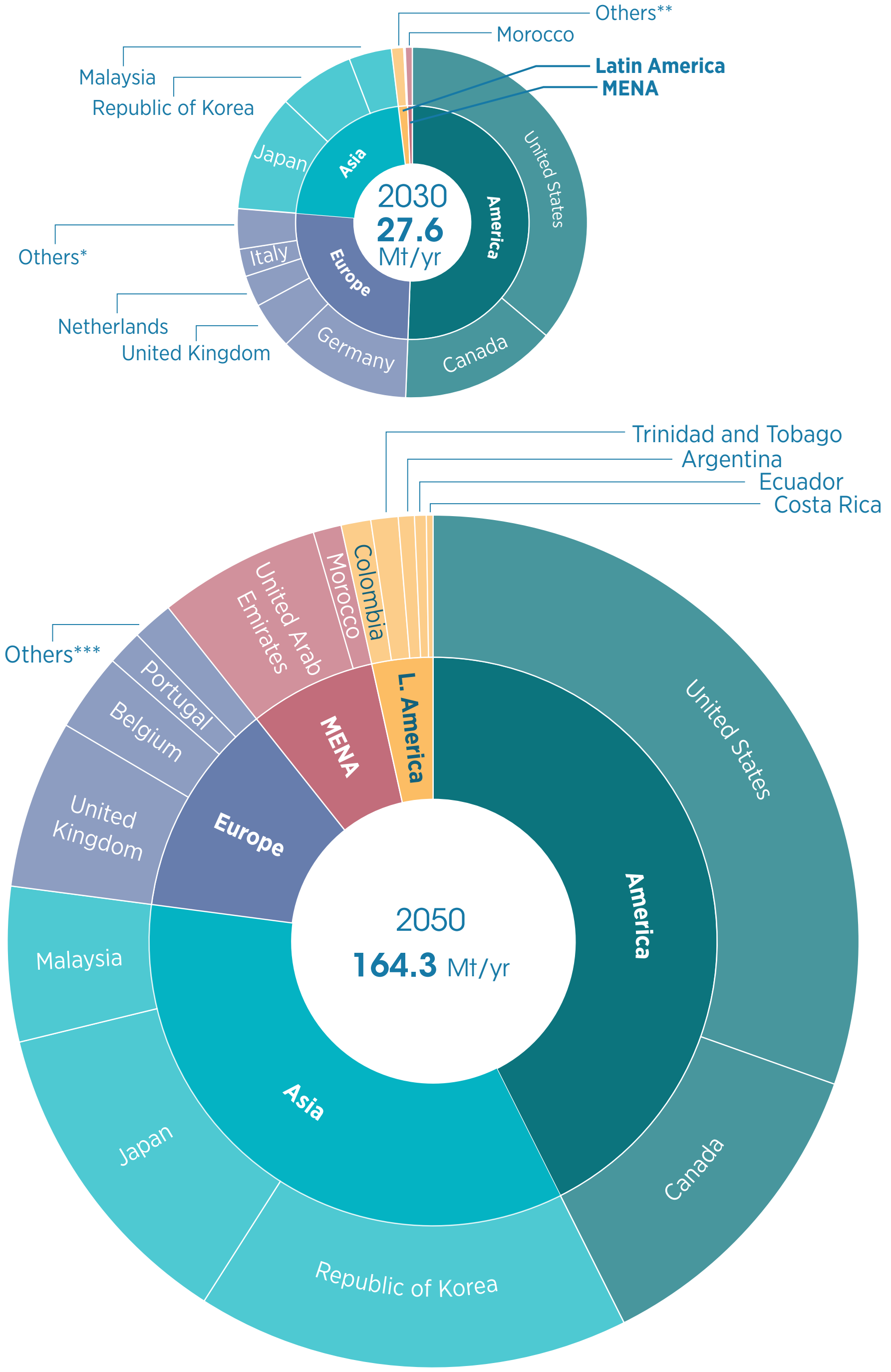
Figure 16 Hydrogen production targets, 2030 and 2050 [Mt/yr]



Notes: *Austria, Czech Republic, Hungary and Ireland; L. America = Latin America; MENA = Middle East and North Africa; SS Africa = Sub-Saharan Africa; Rep. of Korea = Republic of Korea.

On the consumption front, the targets are similarly ambitious: 27.6 Mt by 2030 and 164 Mt by 2050, underscoring the expected growth in demand for green hydrogen, with 23 countries targeting consumption by 2030 and 20 by 2050, 16 of which have laid out plans for both time frames (Figure 17). Some difference between production and consumption targets may indicate a larger role foreseen for import of hydrogen by large consuming nations.

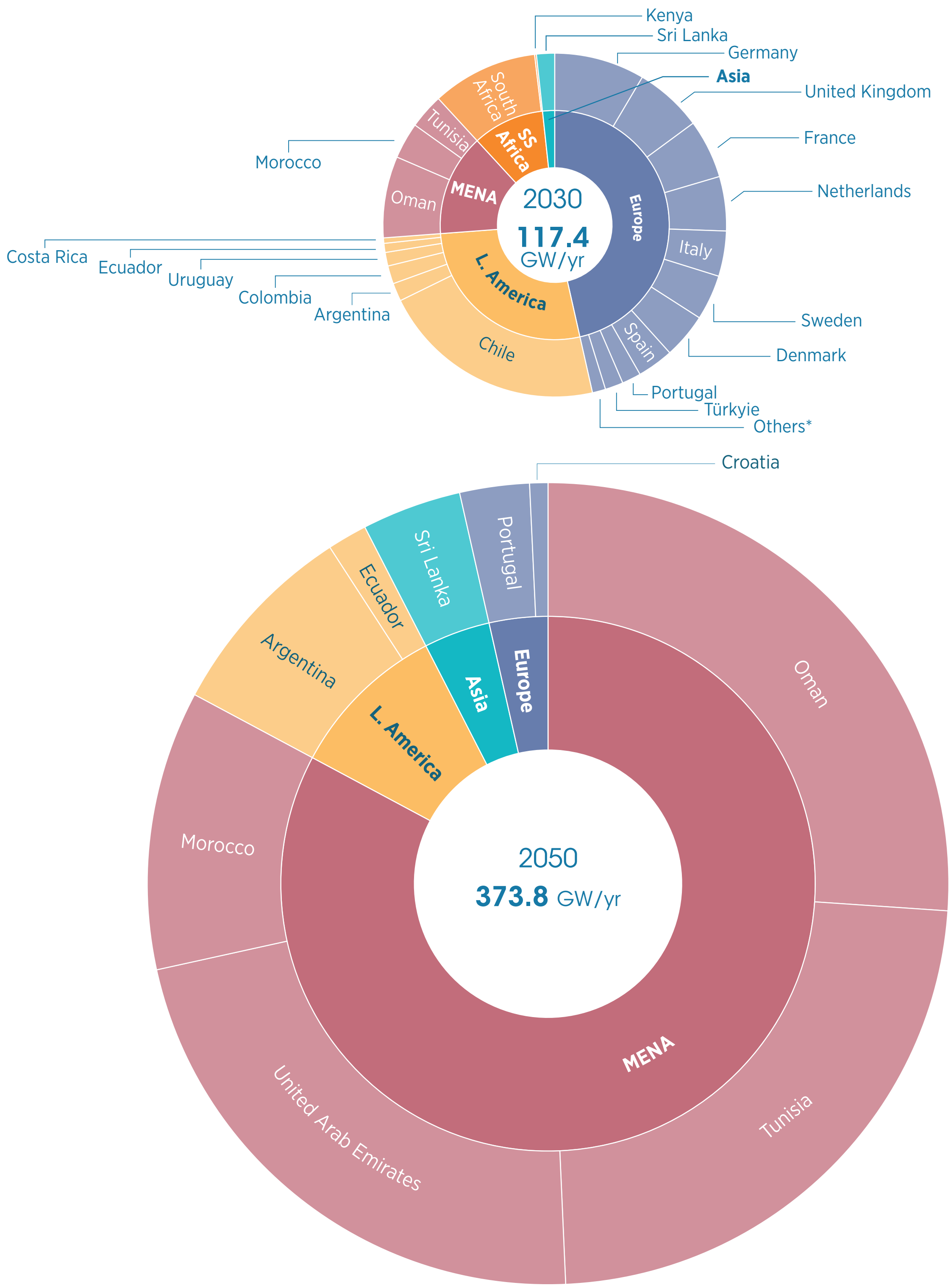
Figure 17 Hydrogen consumption targets, 2030 and 2050 [Mt/yr]



Notes: *Austria, Belgium, Croatia, Hungary, Poland, Portugal and Slovakia; **Argentina, Colombia, Costa Rica, Ecuador and Paraguay; ***Croatia, Hungary, Ireland, Luxembourg and Slovakia; L. America = Latin America; MENA = Middle East and North Africa; SS Africa = Sub-Saharan Africa.

Countries collectively aim for an electrolyser capacity of 117.4 GW by 2030, which more than doubles to 373 GW by 2050. This growth trajectory is supported by 26 countries with short-term targets and 9 with long-term plans (8 of which have targets for both periods) (Figure 18). The most ambitious long term targets are present in the Middle East and North Africa region.

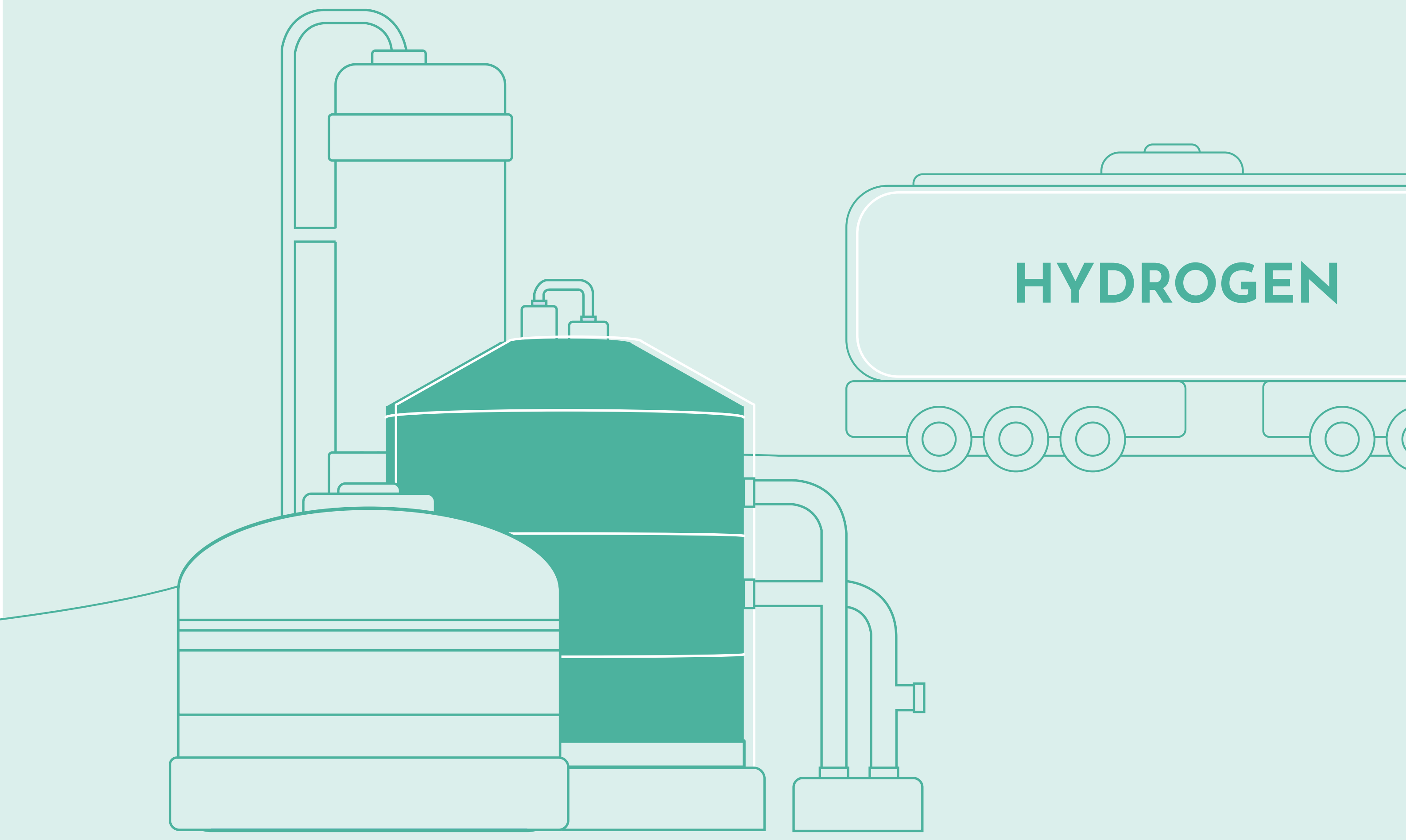
Figure 18 Capacity targets for hydrogen production, 2030 and 2050 [GW]



Notes: *Austria, Belgium, Croatia and Hungary; MENA = Middle East and North Africa ; L. America = Latin America; SS Africa = Sub-Saharan Africa.

PART 3

Policy action



8. What is the problem?
Barrier identification

During and after setting the targets, it is important for policy makers to objectively assess the existing barriers that may impede achieving them. It is possible to conditionally divide these barriers into technological, economic, institutional and social categorisations (Figure 19).

Figure 19 Barrier categorisation

Technological	◦ Immaturity of technologies at scale ◦ Energy and hydrogen losses ◦ Safety concerns ◦ Infrastructure incompatibility
Economic	◦ High costs ◦ Lack of demand of green hydrogen ◦ Lack of suitable end uses ◦ First-mover disadvantage ◦ Lack of personnel and skillsets
Institutional	◦ Unready regulatory framework ◦ Insufficient co-ordination among authorities ◦ Insufficient international co-operation ◦ Lack of policy ambition
Social	◦ Lack of public awareness and acceptance ◦ Hydrogen hype and fear of missing out hydrogen ◦ Lack of investor confidence

It is crucial that policy makers and stakeholders have a clear understanding of the potential and limitations of green hydrogen and can navigate the abundance of information available. This requires a comprehensive analysis of the local resources, market demand, and technological capabilities, as well as a realistic assessment of the costs and benefits of green hydrogen projects. An example of this approach comes from Panama (Box 14).

Box 14 Barriers identification in Panama's hydrogen strategy

Panama's hydrogen strategy provides a detailed description of the procedure for identifying key barriers associated with the development of green hydrogen and its derivatives in the country.

The expected role of Panama in the global value chain of green hydrogen and its derivatives, determined in previous stages of strategy development, was taken into account. The identified barriers were categorised into economic, political, social, technological and environmental aspects. A total of 28 risks were identified, with more than 70% falling under technological or economic categories.

The strategy assessed the impact level of each risk on a scale of four levels (minor, moderate, major or massive) and its likelihood of occurrence on a four-level scale. This creates a metric by which barriers were prioritised based on the degree of threat and relevance for further action. Five barriers with high scores were highlighted: two technological, two economic and one environmental.

These were the challenges in co-ordinating the actions for establishing an operational green bunkering market, involving potential obstacles in strategy execution and market entry; the lack of availability and high pricing of green ammonia for import or local production and for long-haul sectors; the high investment costs associated with equipment replacement/reconstruction and delays in obtaining environmental permits.

8.1 Barrier categorisation

Technological barriers

Immaturity of hydrogen technologies at scale

To some extent, the development of the hydrogen sector has reached industrial maturity. However, while certain hydrogen technologies are highly mature – such as small-scale electrolysis, cryogenic liquid hydrogen storage, hydrogen pipelines and ammonia shipping – others are still under development, particularly in storage, transport and some end use applications. Some of the key technologies are unproven at scale and lack the requisite operating track record for financing and insurance.

Alkaline and PEM electrolysis, for example, are fully commercial. However, neither of these technologies has been installed above the 20-200 MW range, so technological issues at a larger scale are still to be explored. Other electrolysis technologies are not mature. The closest to commercial maturity is SOEC electrolysis, which is still at the prototype/testing stage.

In the realm of hydrogen transport technologies, there is a diverse range of maturity and readiness for commercial application. Gaseous hydrogen transported via truck trailers is already in full commercial use, and new technologies are being brought to maturity, with innovations in materials for better efficiency and safety. Liquid hydrogen truck trailers are also advancing steadily towards widespread commercial adoption. Shipping hydrogen, in contrast, is still at early stages, with only a few pilot examples led by Japan (IRENA, 2021a).

The end-use sectors where hydrogen is currently applied are, naturally, already mature. However, new plant design solutions will be necessary in many cases to change captive steam methane reforming systems with electrolysis-based ones or merchant hydrogen. The production of green steel reached the prototype stage only in 2022, while the production of synthetic fuels is partially in the pre-commercial phase.

Significant energy and hydrogen losses across the value chain

The typical electrolysis system efficiency is roughly 66%, which implies that 1.5 MWh of electricity is required to create 1 MWh of hydrogen. Higher efficiency figures are already within grasp.

The fundamental obstacle for hydrogen transmission and storage is its low volumetric energy density. Each method of producing, treating and transporting hydrogen involves a certain amount of energy and results in energy losses. The greater the energy losses, the greater the demand for renewable power capacity. This would raise the yearly rate of renewable capacity commissioning required to satisfy electricity system decarbonisation objectives.

The compression process needs between 1 and 7 kilowatt hours (kWh) per kilogram of hydrogen, depending on the compression level, while liquefaction requires up to 12 kWh/kgH_2. However, efforts are being made to reduce this consumption down to 6 kWh/kgH_2.

In addition, around 1.65% of the hydrogen is lost during the liquefaction process, and around 0.3% of the liquefied hydrogen is "boiled-off" every day during transit and storage (although technologies are available that can reduce these losses, and it is beneficial to use them). In addition to the physical loss of hydrogen, these losses can make an indirect contribution to global climate change. This issue is even more significant for inadvertent leaks, which can happen in a manner similar to what is currently happening with methane leaks in the natural gas sector.

Ammonia production has a high specific energy consumption (around 55-60% efficiency from power to ammonia), and unless ammonia is the final product, its reconversion back to hydrogen will take an additional 15-20% of the hydrogen content.

R&D is planned to enhance the efficiency of both the generation and conversion of green hydrogen, lowering the overall costs of this decarbonisation approach (IRENA, 2021a).

Safety concerns

Safety concerns have created a barrier to the widespread adoption of hydrogen-related technologies. Hydrogen is a highly flammable and explosive gas, and there have been instances in the past where leaks or malfunctions have resulted in fires and explosions. Hydrogen is often remembered for the Hindenburg disaster. As a result, strict regulations and standards are in place to ensure the safe handling and storage of hydrogen, which can increase the costs associated with its use.

Hydrogen has several characteristics that make it safer to handle and use than traditional fuels. It is non-toxic and has a lighter weight than air, allowing for quick dispersal in the event of a leak. However, some properties of hydrogen need special engineering controls for safe use. Hydrogen has a wide range of flammable concentrations and ignites more easily than gasoline or natural gas, so proper ventilation and leak detection are crucial for safe hydrogen systems. The use of special flame detectors is also necessary, as hydrogen has an almost invisible flame. Similar to methane, hydrogen is odourless, so odourisation will be required for early detection of leaks (however, it is crucial to ensure that these odorants do not compromise fuel cells and other sensitive systems).

To ensure safe hydrogen systems, selecting appropriate materials is important, as some metals can become brittle when exposed to hydrogen. Training on safe hydrogen handling practices and testing of hydrogen systems (such as tank leak tests and hydrogen tank drop tests) are essential to ensure the safe use of hydrogen. As more hydrogen demonstrations occur, hydrogen's safety record will grow and increase confidence in its safe usage, comparable to fuels currently in use. The key focus will be the alignment of relevant technical standards and protocols on a global scale and their strict adherence (Box 15).

These efforts are aimed at overcoming the barrier created by safety concerns and paving the way for the widespread adoption of hydrogen as a clean and sustainable energy source.

Box 15 Standards and safety in China's hydrogen strategy

China's hydrogen strategy, as part of the improvement in the policy and institutional framework of the country's hydrogen sector, places a special emphasis on establishing comprehensive standards and enhancing oversight for safety across the entire hydrogen value chain. Key directions include:

- Facilitating the development and enhancement of fundamental quality and safety standards for hydrogen; infrastructure standards for hydrogen production, storage and transport devices; as well as standards for hydrogen application.
- Encouraging leading enterprises to actively participate in standards development and supporting qualified public groups in the development and publication of relevant standards.
- Strict adherence to mandatory standards in policy development and government procurement, actively promoting recommended standards and corresponding national norms.
- Establishing government service platforms for the verification, testing and certification of products.
- Strengthening research on safety management systems and standards, enhancing safety oversight.
- Implementing primary enterprise responsibility for safe production, departmental responsibility for safety supervision, and local government responsibility for territorial management of hydrogen sector development.
- Promoting the development of advanced technologies, early warning systems, signalling, internet, big data and artificial intelligence for timely early warning of leaks, fatigue, deflagration, to effectively enhance the ability to prevent accidents.
- Strengthening emergency response capabilities, studying and developing plans for emergency response to hydrogen-related emergencies.

Limited compatibility of hydrogen with existing energy infrastructure

Due to the difference in the physical and chemical properties between hydrogen and conventional fuels, existing fossil fuel infrastructure (pipelines, tankers, fuel tanks, filling stations, engines, turbines, furnaces, boilers, burners) is not easily compatible with the requirements of hydrogen infrastructure at scale.

Policy makers need to be aware that switching to hydrogen will require significant adaptation of existing infrastructure (for example, retrofitting natural gas pipelines to allow hydrogen blending in significant volumes, more than a few percent). Energy infrastructure has a lifetime spanning up to half a century, which means that investment decisions now being made must already take into account future hydrogen transition.

Economic barriers

High costs in the hydrogen value chain

In 2023, green hydrogen produced from water electrolysis using renewable electricity had a cost that was around four times the price of grey hydrogen in various countries: USD 4.5/kg to USD 12/kg versus USD 0.98/kg to USD 2.93/kg (BNEF, 2023). The result of the first auction from the European hydrogen bank identified the levelised cost of hydrogen (LCOH) of EU projects to range between USD 6.2/kg (in Greece) and USD 14.2/kg (in Poland) (European Commission, 2024b). While the ratio between grey and green hydrogen costs is can change due to oscillation in natural gas prices, the LCOH of green hydrogen is expected to remain higher than its blue and grey counterparts.

The issue of high cost continues along the whole value chain of hydrogen. The conversion costs will need to be added to the final LCOH. For example, the compression process for fuelling trucks, considering the capital costs of the compression plant and the electricity consumption, adds around USD 1/kg to USD 1.5/kg. Similarly, the liquefaction process could add around USD 2-3/kg of hydrogen. Estimates of the cost of conversion from hydrogen to ammonia in 2030 are in the range of USD 0.4/kg to USD0.9/kg. Reconversion can double or triple these costs; however, ammonia can be used as a feedstock and as a fuel, so this process may not be needed.

Transporting hydrogen generates additional costs, between USD 0.05 and USD 2/kg, depending on the means of transport, volumes and distance. Too-high transport and conversion costs will make it economically unviable to transport green hydrogen, and electrolysers would only be built at a close distance to large demand centres (IRENA, 2021a).

Box 16 Cost barriers in Argentina's hydrogen strategy

Argentina's National Hydrogen Strategy from 2023 outlines detailed plans and projections for the cost of hydrogen production, focusing on both blue and green hydrogen. The strategy is ambitious, aiming to position Argentina as a competitive player in clean hydrogen production. Argentina's strategy recognises the current cost challenges and outlines a multi-faceted approach to overcome these barriers, aiming for a significant cost reduction in hydrogen production by 2050.

The cost of blue hydrogen in Argentina is estimated in the strategy at USD 1.1 to USD 2.1/kg. The cost of blue hydrogen production is greatly influenced by natural gas prices, which constitute 50-70% of the LCOH. Conversely, the cost for green hydrogen varies between USD 2.8 and USD 6.4/kg. This cost depends on the availability of renewable energy resources, with regions such as Patagonia offering more attractive prospects compared to central and north-west Argentina. By 2030, the cost of green hydrogen production is expected to fall to USD 1.7 to USD 2.3/kg, and by 2050, it could further reduce to USD 1.4 to USD -1.7/kg.

Considered key to reducing costs is the advancement in electrolyser technologies, particularly alkaline electrolysers. Argentina aims to master this technology by 2030 to enable large-scale, cost-effective production. Access to financing is considered crucial to close capital and technology investment gaps. This will require the creation of a conducive legal framework and incentives to attract productive investments and technology transfer. Finally, Argentina plans to implement demonstration projects to understand the real costs of low-emission hydrogen production. The strategy includes fostering partnerships between local industrial companies and boosting R&D in key technology sectors.

Lack of demand for green hydrogen

Today there is minimal green hydrogen demand, limited hydrogen infrastructure and a global electrolyser capacity of only a few hundred megawatts. The lack of real green hydrogen demand poses a significant challenge to the widespread adoption of green hydrogen. Offtake agreements, which secure the sale of green hydrogen, are crucial to reduce risk perception and allow the financing of production facilities.

However, the high cost of green hydrogen and the lack of infrastructure to support its use make it difficult for producers to secure buyers. This, in turn, makes it challenging for them to secure financing and invest in the necessary production facilities. As of January 2023, less than 10% of the USD 320 billion in announced investments in hydrogen-related projects (including production and supply, infrastructure, end use and off-take) through 2030 represented real committed capital (Hydrogen Council and McKinsey & Company, 2023).

As of October 2023, only 10% of the planned clean hydrogen capacity by 2030 had secured a committed buyer. Out of 149 offtake agreements for clean hydrogen and its derivatives, only 13% of the agreed-upon volume (equivalent to 1 Mt) had attained binding status. An additional 7% comprised pre-contractual agreements, exhibiting a strong likelihood of transforming into formal binding contracts. The remaining 80% consisted primarily of memorandums of understanding or unspecified arrangements (BNEF, 2023).

Lack of demand of suitable end uses to ramp up the market

The lack of suitable end uses for green hydrogen in the areas with the best resources is a major barrier to its widespread adoption. The Global South, which has abundant renewable energy resources, is particularly impacted by this challenge. Despite the potential for green hydrogen to displace fossil fuels and reduce greenhouse gas emissions, there is a lack of immediate large industrial end uses for this form of energy in these regions. Another obstacle is that in the Global South generally carbon emissions are not priced, which hinders the competitiveness of hydrogen against fossil fuels. Other end uses, such as FCEV buses, would require the development of new infrastructure and end use technologies, slowing the transition.

First-mover disadvantage and stranded assets risk

Early investment in electrolysers (or other technologies across the value chain) may become outdated as the green hydrogen market evolves, and as cheaper solutions emerge. This could result in early adopters having a competitive disadvantage and their investments becoming stranded assets.

This could result in large losses for investors and a significant amount of unproductive capital tied up in stranded assets. Investors would then be asking themselves if it does make sense to invest in capital-intensive, complex, risky and long-term projects, if they risk turning into stranded assets before the payback period.

This first-mover disadvantage is a significant challenge, highlighting the important need for careful policy planning and risk management in the transition to a low-carbon energy economy. On the other hand, early adopters have a competitive advantage of learning by doing and being able to build subsequent facilities faster, cheaper and more efficient.

Lack of personnel and skillset

There is a shortage of experienced individuals who can design, implement and maintain hydrogen systems; draft proper technical standards, strategy and regulatory frameworks; and manage project development to fulfil the growing demand for green hydrogen. This lack of skill and experience may make the shift to hydrogen technology difficult and too slow for countries, enterprises, and organisations, as well as raise the expenses connected with its use. To remove this hurdle, there is a rising movement to build hydrogen technology and policy training and education programmes. The hydrogen sector will only be able to fulfil its full potential if investments are made in the education and training of future generations of hydrogen experts.

Institutional barriers

Regulatory framework not ready for hydrogen sector

The absence of a comprehensive regulatory framework specifically tailored to the hydrogen sector presents a major challenge to its widespread adoption. Existing regulations and standards in the field of hydrogen technology are fragmented and inconsistent across jurisdictions, creating uncertainty and confusion for businesses and organisations looking to invest in hydrogen technology. For example, hydrogen is often considered in national technical regulations as an explosive gas that must be handled very carefully and only in special industrial areas. Such a status is definitely very far from the role of a new global energy carrier.

Until a consistent and comprehensive regulatory framework is established, the growth of the hydrogen sector will continue to be hindered by these regulatory barriers.

Lack of co-ordination among national public bodies

When public bodies work in silos and do not effectively co-ordinate their efforts, perhaps with conflicting agendas, it can result in duplicated efforts and an overall lack of cohesion in the regulation of the hydrogen sector. This can lead to inefficiencies, higher costs and a slower pace of growth in the industry.

The lack of readiness in the regulatory framework and insufficient co-ordination among government bodies pose a threat to the timely issuance of permits for specific investment projects. This phenomenon currently hinders the deployment of renewables and has the potential to become a significant impediment to the widespread adoption of hydrogen in the future.

Lack of policy ambition

When implementing policies that translate climate commitments into reality, there is a risk of the adoption of sub-optimal policies.

Decarbonisation policies often promote a gradual pathway for each sector (for example, gradual use of renewable-based solutions or energy efficiency measures). The goal of reaching zero emissions requires a very different mindset and, in some cases, progressing with the "gradual reduction" mindset risks locking in emissions. The "gradual reduction" mindset, in fact, enables a market for less carbon-intensive but still fossil fuel-based solutions. Blue hydrogen with partial CCUS could be an example, and electrolytic hydrogen fuelled by fossil-based electricity could offer a lifeline for fossil fuels.

These solutions create additional transitional barriers, as adopters of the more efficient (but still fossil fuel-based) solutions aim to complete their investments' lifetime instead of changing technology as new, more restrictive policies are adopted.

This situation will require further actions to eliminate the remaining emissions when more ambitious climate change objectives are later adopted, creating additional government expenditure and stranded assets that pile up as the infrastructure of the fossil fuel era.

Investment decisions in industry have a long-term impact due to the high capital costs and long useful life of industrial assets. These investment decisions are also urgent: only one investment cycle for large industrial asset exists before 2050, and new low-carbon technologies must be the next recipient of investment to avoid carbon lock-in within the limited time frame to avoid climate catastrophe (IRENA, 2022i).

Lack of co-ordination at the international level

A lack of international co-ordination can result in conflicting plans and regulations across different countries, causing difficulties for businesses to operate on an international level.

Additionally, the lack of a harmonised approach can lead to multiplication of efforts, increased costs and a slower pace of growth in the green hydrogen industry. It can also result in different standards for the production, storage, and transport of green hydrogen, making it difficult for businesses to expand their operations across borders.

Social barriers

Public awareness and acceptance

Public awareness and understanding about green hydrogen are critical factors for its widespread adoption and growth. A lack of awareness and understanding can result in limited investment, fewer trained professionals and slow deployment of hydrogen infrastructure. The general public's perception and acceptance of green hydrogen also play a crucial role in its market growth. Unfortunately, misunderstandings and misconceptions about hydrogen technology, its safety and its impact on the environment can hamper public acceptance.

The failure to address these misperceptions and misconceptions can prevent the realisation of a social contract on green hydrogen and slow the growth of the green hydrogen market.

Hydrogen hype and “fear of missing out hydrogen”

Despite the quick growth in the number of hydrogen studies and conferences, people often do not have the opportunity to navigate this information flow and learn how to make the right decisions.

This creates the risk of hydrogen “hype”, where the potential of green hydrogen is overstated and leads to unrealistic expectations. On the one hand, hydrogen is sometimes being treated almost as a “silver bullet” capable of immediately solving all urgent problems with decarbonisation, economic growth and global competition simultaneously. On the other hand, there is a tendency to underestimate the effort that would be required for a hydrogen transition at scale. Additionally, policy makers may experience the “fear of missing out” in relation to hydrogen feeling pressure to invest in the technology because other countries or stakeholders are doing so, copying the goal setting and approaches of other players without fully understanding its limitations and feasibility in their region.

Moreover, there is a trend of declarative desire for leadership in which everyone is going to become a global leader in the future supply of hydrogen, green steel or electrolysers – leaving for later the answers to the question of how this front-runner will compete with dozens of other such “leaders”.

Such phenomena can lead to overambitious, unrealistic target setting, poorly designed policies, and investments that are not aligned with the actual market demand and technological capabilities. This brings the risk of misallocating resources and pursuing projects that are not economically viable or technically feasible – losing time, political capital and public acceptance.

Lack of investor confidence

Lack of investor confidence poses a significant barrier to the development and implementation of green hydrogen projects. This scepticism can stem from the combination of the aforementioned barriers but can be exacerbated by the lack of a clear policy guidance.

To address these issues, policy makers can play a crucial role by setting the vision and direction and informing about the targets, the priorities and the policies. In this, the drafting of a hydrogen strategy is key. Building partnerships between public and private sectors can also help in pooling resources and sharing risks, thereby boosting investor confidence in green hydrogen initiatives within their borders.

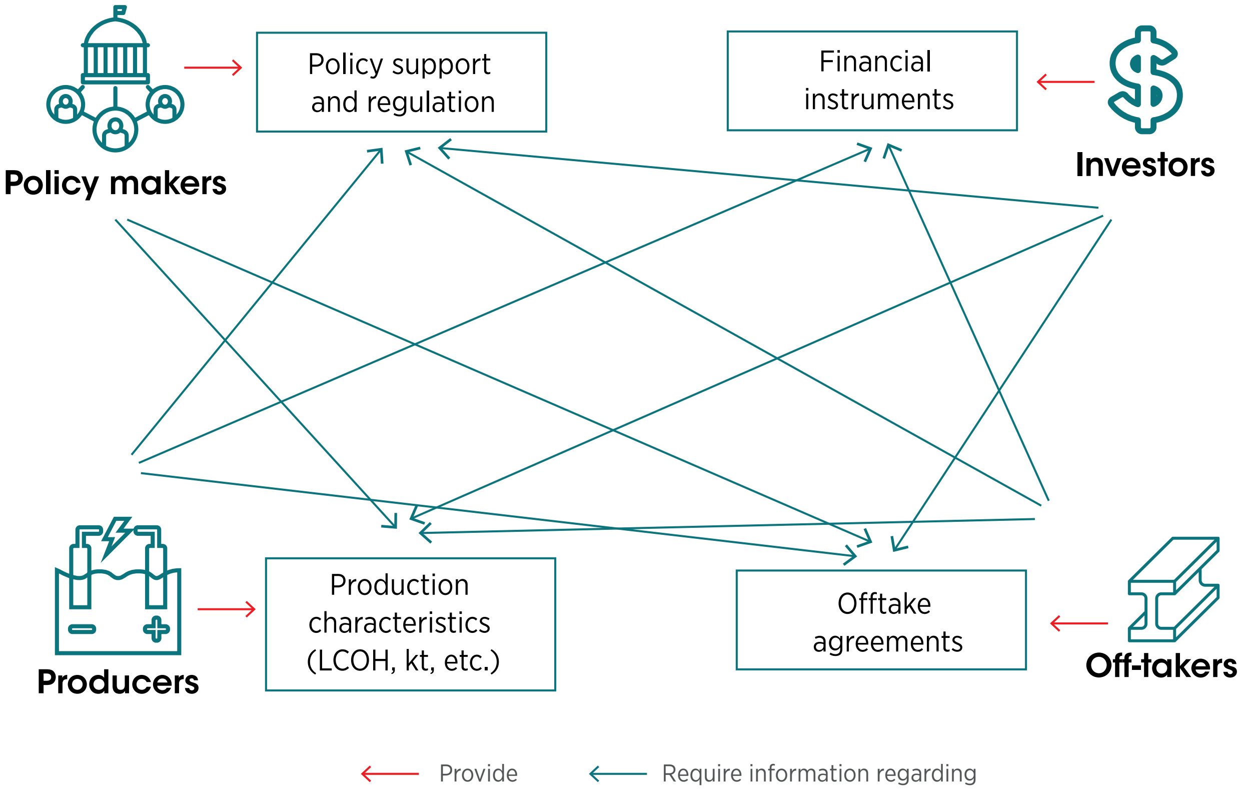
8.2 The green hydrogen deadlock

All the barriers presented above interact with each other. This creates a peculiar situation, as each of the players may be focused on solving a specific issue, but needing assistance, information, data, or commitment from other players, who in turn are focusing on a different sub-set of issues and unable to share data.

This creates the **green hydrogen deadlock** (Figure 20). In this situation, potential off-takers (consumers) and suppliers in the green hydrogen sector are unable to move forward with their plans due to a lack of essential information and resources. Both parties are dependent on each other to provide crucial details and commitments. The potential off-takers require information about the price, physical properties and quantity of green hydrogen from the potential suppliers. They need this information to assess the feasibility and economic viability of incorporating hydrogen into their operations. Without clarity on these factors, they cannot commit to purchasing hydrogen or integrating it into their systems.

On the other hand, potential suppliers, often electrolyser developers and operators, are hesitant to deploy their electrolysers without firm offtake agreements. These agreements assure them of a reliable market and demand for the hydrogen they produce. Without such agreements in place, they face the risk of investing in expensive infrastructure without a guaranteed return on investment.

Figure 20 The green hydrogen deadlock



To break the deadlock, both parties require knowledge of the support policies, standards and regulations governing green hydrogen in the jurisdictions where they operate. Policy clarity and stability are crucial for businesses to make informed decisions and assess the potential risks and benefits of green hydrogen projects. However, in cases where policy makers lack experience in hydrogen technologies, the creation of supportive policies becomes more challenging and time-consuming. They would need information from off-takers and suppliers to facilitate policy making, but the scarce experience in the field from these players makes providing such information more arduous.

Finance institutions can also play a significant role in providing funding for green hydrogen projects. They require comprehensive and accurate information about these projects to evaluate the associated risks and make informed investment decisions. The lack of clarity and commitments between off-takers and suppliers creates uncertainty, making it challenging for finance institutions to assess the viability of these projects and allocate resources effectively. Lack of regulation and policies only increases the risk perceived by these financial institutions.

Another aspect of the deadlock is the need for infrastructure development. The establishment of hydrogen supply and demand points, including production facilities, storage, transport, and distribution networks, depends on the anticipated supply and demand volumes. However, without clear commitments from both off-takers and suppliers, it becomes difficult to determine the necessary infrastructure requirements and plan for their development.

To overcome the green hydrogen deadlock, collaboration and information sharing among all stakeholders are crucial. This includes policy makers, potential off-takers, suppliers and finance institutions. Clear and supportive policies need to be developed to provide a conducive environment for hydrogen deployment. Off-takers and suppliers should engage in transparent discussions to establish offtake agreements and ensure clarity on the price, quantity and physical properties of the hydrogen. Infrastructure planning should be based on anticipated supply and demand, and finance institutions need access to accurate project information to make informed investment decisions. Breaking the deadlock requires a co-ordinated effort and collaboration among all actors involved in the hydrogen sector.

Policy makers can contribute to this by intensifying the interaction among stakeholders (see section 3) and selecting optimal measures for managing the hydrogen sector (see section 9).

9. How? Measures and governance of the hydrogen sector

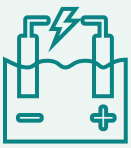
This section outlines practical methods for anticipating and implementing future actions in line with strategic goals.

While strategies offer a vision for the future, their success hinges on concrete policies and interventions. These policies are instrumental in overcoming barriers, leveraging financing mechanisms, setting priorities and engaging stakeholders. The ultimate aim is to transform strategic analysis into impactful solutions that realise the objectives of the strategy.

In the context of green hydrogen, IRENA has made significant contributions through its research and publications. These works provide extensive insights into policies fostering green hydrogen adoption. This section does not delve into these works in detail; rather, it directs readers to IRENA's primary publications for comprehensive information.

Table 4 presents the policies discussed by IRENA, categorised for a concise overview of the policy landscape in green hydrogen.

Table 4 Main policies for green hydrogen deployment

Category	Specific policy instrument	Source
Direct financial support for electrolysers 	Grants	(IRENA, 2021a)
	Auctions (per MW)	(IRENA, forthcoming)
	Fiscal incentives	(IRENA, 2021a)
	Loans	(IRENA, 2021a)

Production support mechanism	Feed-in tariffs	(IRENA, 2021a)
	Auction (per kg)	(IRENA, forthcoming)
	Fiscal incentives	(IRENA, 2021a)
	Price of electricity policies	(IRENA, 2021a)
Hydrogen infrastructure planning and support	Financing	(IRENA, 2021a; UNIDO, IRENA and IDOS, 2023)
	Planning	(IRENA, 2021a; UNIDO, IRENA and IDOS, 2023)
	Taxation	(IRENA, 2021a; UNIDO, IRENA and IDOS, 2023)
	Regulation/governance	(IRENA and WEF, 2021; UNIDO, IRENA and IDOS, 2023)
Demand-side support	Bans and mandates	(IRENA, 2022i)
	Bilateral auctions	(IRENA, 2022i)
	Quotas	(IRENA, 2022i)
	Quotas of products	(IRENA, 2022i)
	Carbon Contracts for Difference	(IRENA, 2022i)
	Tax for products	(IRENA, 2022i)
	Carbon Border Adjustment Mechanism	(IRENA, 2022i)
	Public procurement	(IRENA, 2022i)
Regulation	Standards	(IRENA and WEF, 2021)
	Certification	(IRENA and WEF, 2021)
Local content manufacturing	Manufacturing support	(IRENA, 2021a; UNIDO, IRENA and IDOS, 2023)
	Targets for local content	(IRENA, 2022i)

In the realm of strategic policy making, a critical question may arise: "What is the added value of incorporating a specific policy promise within a strategic document?" This section delves into the multi-faceted answers to this question, exploring the implications for various policy inclusion in strategic frameworks. It is followed by an analysis of the temporal dimension of such commitment, or the "phase approach", and a presentation of the governance systems put in place to achieve the policy implementation.

9.1 Strategic impact of commitments

The value of policy expectation within strategic frameworks is crucial. Strategies can provide an insight on how policy makers expect a change to happen, and this can have profound impact. This section addresses this topic by providing two distinct perspectives. The first is impact-enhancing investor confidence, a critical factor for the success and growth of green hydrogen initiatives. The second perspective focuses on the concept of strategic windows of opportunity for policy implementation. This approach involves creating the opportune moments for effective policy action.

Policy commitment and investor confidence

Developers and investors seek assurance of a stable regulatory environment that guarantees that their investments are safe. This is particularly important for green hydrogen, which is still in its nascent stages and requires significant capital investment. By committing to a supportive and predictable policy framework, governments can attract more investments in green hydrogen projects.

A hydrogen strategy can be a public commitment by the government to take a series of actions to transform a vision into a reality.

A strong, future-proofed governmental commitment to transitioning the hydrogen sector will reduce investors' perceived risks and lower the risk premiums that they expect. That commitment is typically expressed in the hydrogen strategies, and the presence of promised measures can enhance the confidence of the translation of government commitment into implementation.

When used effectively, commitment can lead to a more consistent and continuous policy environment, as governments are likely to pursue a steady course of action aligned with their stated commitments. This means that the agenda and priorities of the government on the specific sector become a reflection of these promises.

Commitment influences the final form of policies, as objectives or methodology to achieve a certain outcome may be part of the commitments made. When policy proposals align with publicly stated commitments, they can create a sense of accountability and credibility. This, in turn, fosters trust among investors and stakeholders, ensuring that the policies will be adhered to, and goals will be pursued diligently.

Committing to policies in a hydrogen strategy can bolster a country's standing in the international market. By leading in regulatory frameworks and investment incentives, a country can position itself as a pioneer in the green hydrogen sector, attracting not only investment but also talent and technological innovations (Box 17). One of the risks associated with this approach is the potential for governments to make overly ambitious or unrealistic commitments, which can lead to investor disillusionment if these are not fulfilled. Policy makers may underestimate the effort required to effectively administer these policies.

The green hydrogen sector, with its unique barriers and blind spots, demands a nuanced approach to regulation. Delays or failures in executing commitments can exacerbate the reputational issues already present in the sector. Any delay in implementing commitments can then deter early investments. This is a critical factor for a nascent technology such as green hydrogen, where early investments are essential for technology development and market growth.

Box 17 The Inflation Reduction Act in the United States

The Inflation Reduction Act (IRA) is a US federal law that aims to curb inflation through different policy measures, including investing in domestic energy production while promoting clean energy.

The IRA encourages the production of low-carbon hydrogen* by offering financial assistance to producers. Under investment tax credits (ITC), project developers can receive a tax credit of up to 30% of the investment expenditure incurred for purchasing electrolysers and other necessary equipment. In addition, production tax credits (PTC) provide financial support of up to USD/kg. The exact amount of support depends on factors such as the overall greenhouse gas emissions over the project's lifetime and socio-economic considerations such as wage and apprenticeship requirements. Eligible producers can avail themselves of the production tax credit for a period of 10 years.

Furthermore, the IRA allows for the accumulation of support. This means that hydrogen producers can utilise subsidised renewable electricity or even receive support for their on-site renewable energy systems. The IRA is further supported with around USD 9.5 billion under the Infrastructure Investment and Jobs Act, providing assistance for clean hydrogen hub development and R&D activities.

Revenue volume certainty, combined with the bipartisan support that hydrogen projects are receiving, is positioning the United States to be a leader in green hydrogen production. Competitiveness and a stable outlook on the supporting mechanisms has increased investor confidence, with increased perception that the IRA may draw green hydrogen investments away from other markets.

* *Low-carbon hydrogen is defined as hydrogen that emits less than 4 kg of CO_2 equivalent per kilogram of hydrogen produced at the point of production.*

This approach may also involve engaging with stakeholders to balance commitments with the practicality of policy execution (see section 3) with regular assessments of the policy impacts, and adjustments as necessary. Governments need to maintain a long-term vision for green hydrogen while implementing short-term actions that build the foundation for this vision.

European countries, in particular, have drafted hydrogen strategies that present detailed policy commitments; see Box 18 for an example in Spain.

Box 18 The 60 measures in Spain's green hydrogen strategy

Spain's government launched its green hydrogen strategy in 2020. The strategy describes the value chain and the opportunities created by green hydrogen for Spain. It then presents 60 measures, encompassing a broad range of regulatory, sector-specific, cross-sectoral, and R&D aspects, all aimed at establishing a green hydrogen sector. This concise overview highlights the pivotal aspects of the strategy.

- **Regulatory instruments:** The set of measures (five in total) aims to streamline administrative processes and eliminate regulatory barriers to hydrogen production. Key measures include simplifying procedures for small-scale green hydrogen installations.
- **Sector-specific instruments:** Focusing on sector-specific applications, the set of measures (29 in total) underscores the use of green hydrogen in industries such as iron and steel production, and chemical manufacturing. The measures include the establishment of a national statistical system for hydrogen consumption and production and assess the feasibility of setting renewable hydrogen quotas for sectors where electrification is less likely to provide a decarbonisation solution.
- **Cross-sectoral instruments:** In a bid to foster widespread adoption of green hydrogen, the strategy includes 16 measures for promoting its use and for integrating hydrogen into Spain's existing energy networks, with plans to enhance compatibility of infrastructure and end uses.
- **Boosting research and development:** A final section is dedicated to advancing R&D in the field of hydrogen technology. The ten measures include funding research on large-scale electrolysers and promoting collaboration with European partners. The government aims to establish centres of excellence for hydrogen storage research and to explore the potential of hydrogen turbines in aviation.

De-risking commitment for industrial development

A sub-set of the policy commitments described above is the de-risking commitment for industrial development. This approach combines elements of state intervention and private sector engagement to promote economic development, and it can be noticed in particular in hydrogen strategies of developing countries.

De-risking for industrial development is a concept in which the role of the state is to facilitate the mobilisation of private (potentially foreign) capital for developmental projects. It is based on the idea that the state can play a key role in creating an environment that reduces risks for private investors, thereby attracting investment into strategic development sectors. This approach is seen as a response to fiscal constraints or lack of funds that can make goals difficult to achieve through subsidies and regulation alone.

Practically, de-risking for industrial development manifests through various partnerships and financial instruments. One common method is through public-private partnerships, where the state collaborates with private entities to fund and implement projects. Fiscal de-risking involves using public funds or concessional resources to secure predictable returns in various asset classes, including infrastructure. This involves tax incentives, managing risks in public-private partnerships, and guaranteeing prices or demand in specific agreements.

Governments might seek to offer guarantees to private investors against certain risks, such as political instability or currency fluctuations, to make investment projects more attractive. Additionally, development banks and international financial institutions often play a crucial role in providing concessional loans and grants that are blended with private capital to finance projects. This blending of public and private funds helps to lower the overall cost of capital for projects, making them financially viable and attractive to private investors.

Another aspect of de-risking for industrial development is the creation of special financial vehicles or funds to support specific initiatives. For example, governments may establish funds to attract both public and private investments in areas such as green hydrogen, where the capital required for projects is substantial. These funds may deploy concessional capital to mobilise private investments and jump-start industrialisation ambitions. The strategy involves working closely with project developers to address operational and technology risks and to facilitate offtake agreements to lower market risk, often using blended financing solutions to support different project phases. In some cases, strategies are explicit in their attempt to attract foreign investments, for example in Namibia (Box 19).

Box 19 SDG Namibia One Fund

The SDG Namibia One Fund, launched at the 2022 United Nations Climate Change Conference (COP 27) in Sharm El-Sheikh, Egypt, is a pioneering initiative to foster the development of a green hydrogen sector in Namibia. This innovative blended finance platform, a collaboration between the Environmental Investment Fund of Namibia, Climate Fund Managers (CFM), and Invest International from the Netherlands, aims to accelerate the development of Namibia's green hydrogen sector. The fund will channel all green hydrogen financing in the country, leveraging Namibia's excellent conditions for generating renewable electricity through solar and wind power.

CFM, one of the managing partners, is an investment manager focused on using blended finance to attract investment in high-impact sectors in emerging economies. Invest International specialises in impact investment, supporting Dutch and international projects that align with the Sustainable Development Goals, with a focus on project finance and export finance. The Environmental Investment Fund (EIF) of Namibia was established by the Namibian Parliament to support sustainable natural resource use. EIF works with various stakeholders, including non-governmental organisations, government bodies, community organisations, and the business community, to ensure the successful integration of their projects within Namibia's socio-economic and environmental development framework.

The fund's structure is designed to attract both public and private capital, supporting the implementation of green hydrogen projects from the early development stage through construction and operation. Invest International, acting as an anchor investor, contributes an initial grant of USD 43 million (EUR 40 million), with the fund's total envisaged size reaching USD 1.07 billion (EUR 1 billion). This strategic approach enables the private sector to access capital at various project stages, aiming to bolster Namibia's transition to green energy (Climate Fund Managers, 2022; Gabor and Sylla, 2023).

The de-risking strategy can be perceived as a method for governments to guide industrial development without fully implementing industrial policies.

In nations with industrial policies, investments in key sectors such as green industry are typically managed through various approaches. These include favourable loans, public procurement, encouraging exports through subsidies and competitive currency values, and temporary protection for infant industries. Alongside these supports, regulations and mandates are also in place, such as strict performance standards related to production volume, competitiveness, technology advancements and export goals. Industries benefiting from industrial policies have to match national strategic objectives to receive further funding (Amsden, 2001; Wade, 2018).

The **de-risking strategy** involves instead flexible conditions focused on delivery rather than stringent performance criteria. By covering risk, the state takes on the duty to compensate private investors if market changes affect their expected returns. In a de-risking strategy, tightly managing how credit is used by strategic industries is much harder. This method views both local and international financiers as partners. In this partnership, their expectations about risk and returns are discussed and negotiated, rather than using methods to control how private companies in key sectors interact with these financiers (Gabor and Sylla, 2023).

The global economic landscape is increasingly favouring the adoption of full-fledged industrial policies, in particular for green industry. This trend is a response to various economic challenges and opportunities, and it represents a shift towards more strategic and active government involvement in key industrial sectors. Countries around the world are recognising the importance of these policies as essential instruments for shaping economic growth and development (CRS, 2023; WEF, 2023). The Carbon Border Adjustment Mechanism, adopted by the European Union in 2023, is an example of such a trend, where industrial policy making is paired with decarbonisation goals. Developing countries exploring their role in green hydrogen therefore have a new (old) set of instruments at their disposal, which would allow them to better control the development of the green hydrogen sector.

9.2 Phases

Timelines are often established in hydrogen strategies. As the penetration of green hydrogen technologies increases and as costs come down, many countries have recognised that policies need to evolve accordingly. A phased approach is often used to reflect the expected evolution of the hydrogen sector and its policy needs along with the increased deployment of green hydrogen.

Setting up policy timelines helps provide clarity and transparency to all stakeholders involved about when policies are expected to be adopted. This can enable co-ordination among various government agencies and other stakeholders, informing on when specific actions will be needed. Clear timelines provide a sense of predictability, and investors can evaluate the risks and returns associated with long-term investments, based on the anticipated policy milestones and timelines. A phased approach, if properly designed, then serves to increase investor confidence in the strategy.

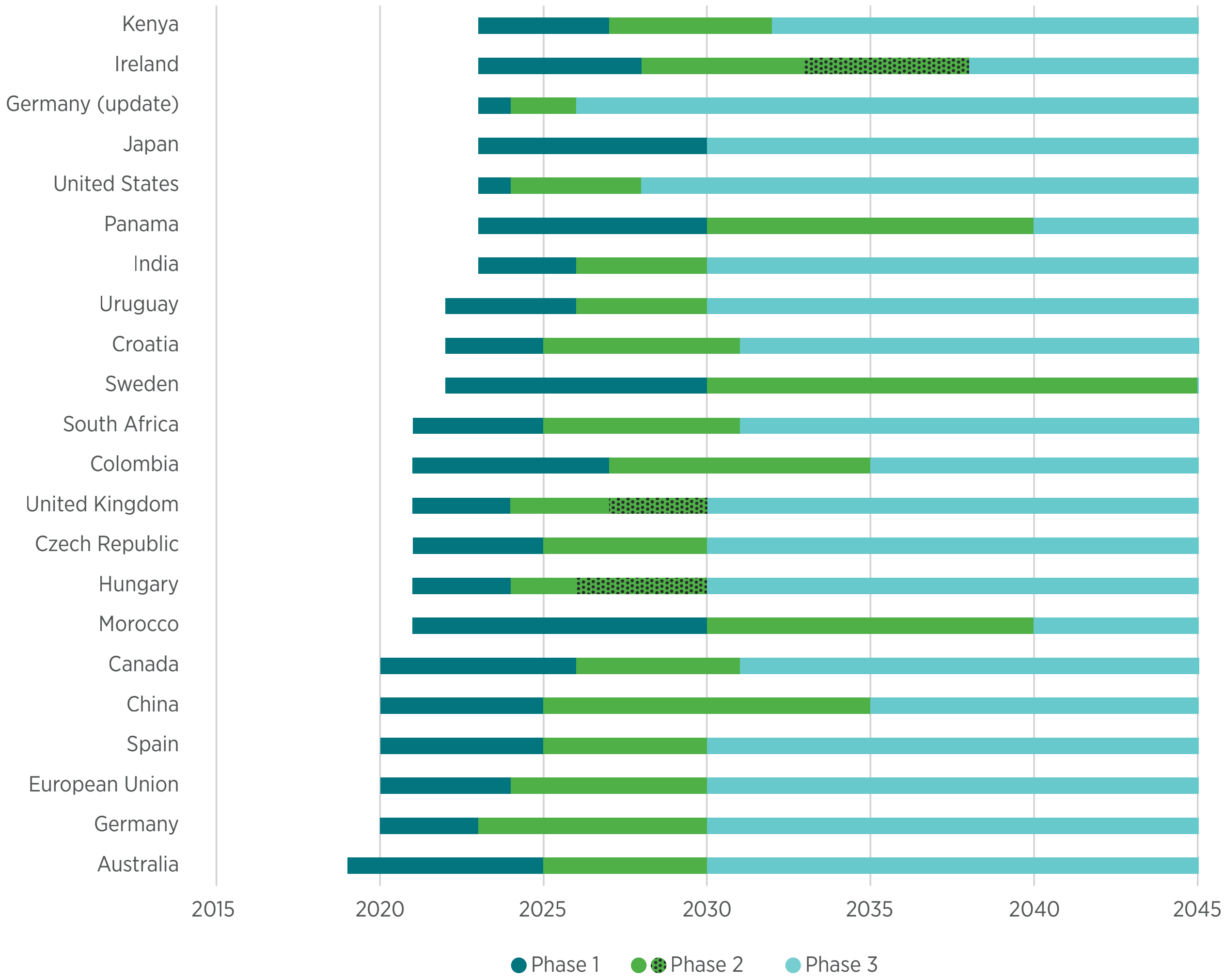
The phased approach allows for tracking progress, evaluating the effectiveness of implemented measures and assessing whether policy goals are being achieved within the defined time frames. If certain milestones are not met as planned, policy makers can identify bottlenecks, adjust strategies and take corrective actions to ensure the policy's success.

It is possible to identify a trend in the phased approach. In many examples of national hydrogen strategies (Figure 21), phases follow this structure:

- **Phase 1: Technology readiness.** At this stage, green hydrogen is a niche technology with little use except in demonstration projects; it is mostly produced on-site with limited infrastructure development. The "software" part is set up in this stage: governance, standards and regulation are often mentioned to be solved in this stage. Deployment of the first MWs of electrolysis and receiving positive societal acceptance signals are the objectives of policy makers.
- **Phase 2: Market penetration.** At this stage, some applications are expected to be operational and able to prove what green hydrogen can do and at what cost. This stage is where most of the supporting policies take place, in each part of the hydrogen value chain.

- **Phase 3: Market growth.** At this stage, green hydrogen is expected to be a widely used energy carrier and is close to reaching its full potential. It has become competitive both on the supply side and in its end uses. Direct incentives are no longer needed for most applications, and infrastructure is in place for transporting it. The policy maker's role is to make sure green hydrogen is the only solution adopted.

Figure 21 Timelines of national strategies by phases



Note: "Germany" refers to the 2020 National Hydrogen Strategy, "Germany (update)" refers to the National Hydrogen Strategy Update. Hungary, Ireland and United Kingdom split the "Phase 2" period in two separate phases, here represented in dotted areas.

A significant trend across a majority of hydrogen strategies is the projection of 2030 as the year when the green hydrogen market reaches "Phase 3". This reflects a consensus in strategies that by the end of the present decade, green hydrogen technologies will have sufficiently advanced, costs will have decreased, and the market will have expanded to a level of robustness and stability; policies needed by then will be only for "maintenance". The focus of many strategies is on achieving a critical mass in terms of technology deployment, market penetration and infrastructure development by this time.

However, some of the more recent hydrogen strategies have adjusted their timelines, moving their goal posts further into the future. This may indicate a recalibration of expectations in light of technological advancements, market dynamics and policy developments. Notably, the first German hydrogen strategy, drafted in 2020, presented the measures for Phase 1, defined as "the phase-up phase", up to 2023, by which time the ramp-up for a well-functioning domestic market was seen to start, while during Phase 2 an international market would gradually build. In June 2023, an updated strategy was presented. In this case, to achieve a similar objective (with an increased target for installed electrolyser capacity), the measures had to be redrafted in short-term (within a year), medium-term, and long-term measures, providing an even more precise timeline for the expected policy actions. Another example of a strategy update is the Japanese one (Box 20).

Box 20 Japanese hydrogen strategies: evolution of phases and goals

The first Japanese Hydrogen Strategy of 2017 (Strategy 2017) was built upon an earlier document, the Strategic Roadmap for Hydrogen and Fuel Cells, adopted in June 2014 (Roadmap 2014).

Roadmap 2014 envisioned a phased approach. Phase 1 included a plan for the dramatic expansion of hydrogen use through the rapid deployment of stationary fuel cells and FCEVs, aiming to position Japan as a leader in the global market. In Phase 2 (by the latter half of the 2020s), Roadmap 2014 aimed for the full-fledged introduction of hydrogen-fired power generation and the establishment of a large-scale hydrogen supply system. Phase 3, targeted for 2040, aimed to achieve a completely CO_2-free hydrogen supply system.

Strategy 2017 introduced more specific quantitative targets, particularly for the first phase (by 2030). These targets focused primarily on hydrogen mobility, intending to increase the number of fuel cell cars to 40 000 units by 2020, 200 000 units by 2025 and 800 000 units by 2030. It also aimed to have 100 FCEV buses by 2020 and 1,200 by 2030, along with expanding the number of hydrogen fuelling stations to 160 by 2020 and 320 by 2025.

The first phase of Roadmap 2014 and Strategy 2017, which focused on deploying hydrogen mobility, has effectively remained unrealised. Although the FCEV bus target was met, only around 7 500 fuel cell cars had been sold as of October 2023 (IPHE, 2023). Nevertheless, medium- and long-term goals for the second and third phases are not being reconsidered in the direction of reduction. The new Japanese strategy, adopted in summer 2023, focuses on two phases instead of three: the first until 2030 and the second until 2050. Long-term quantitative targets in Strategy 2030 have been revised upward; for instance, the target for hydrogen consumption is set at 3 Mt by 2030, 12 Mt by 2040, and 20 Mt by 2050, and the goal for the deployment of stationary fuel cells is set at 3 million units by 2030.

Since the early years of green hydrogen strategies, there was not an alignment between the timelines of hydrogen exporting and importing countries. Importing countries have sizable targets for imports from 2030, with the notable example of the European Union (10 Mt imported by 2030). Morocco, for example, considers "ambitious" the target to achieve export of hydrogen and its derivatives before 2045, when it sees it as more possible for exports to actually start. Colombia considers starting the export of hydrogen only after 2030. Trinidad and Tobago does not consider producing green hydrogen before 2030, and exporting it only after the country's own (sizable) consumption is covered. Namibia expects to produce only 1-2 Mt of green hydrogen by 2030, but no clear export targets are stated. Kenya does not expect to assess export opportunities before 2028 (during Phase 2). South Africa, while aligning its vision to other countries with 2030 as the year the hydrogen market may reach maturity, would consider implementing its export strategy (including commercial export) only after 2030.

The misalignment in timelines, volumes and ambitions between hydrogen importing and exporting countries reflects a combination of developmental, technological, economic and policy challenges. In particular, it may reflect the fact that potential exporting (developing) countries may need more time than importing (developed) ones to 1) ramp up their hydrogen production; 2) decarbonise their own hydrogen consumption; and 3) establish an export-oriented hydrogen infrastructure, while ensuring that their future hydrogen sector maximises the local benefits.

Chokepoints

The strategic implementation of hydrogen policies, as outlined in various national strategies, highlights the complex interplay between technology development, market dynamics and policy frameworks. The phases presented above are necessary once it is recognised that the hydrogen sector is an evolving one.

Each phase of this life cycle – from technology readiness and market penetration to market growth – may be marked by one of more achievements to reach in order to pass to the next phase.

One recurrent achievement identified is the cost compression of electrolysers and renewable energy. The Colombian strategy envisages that hydrogen will begin to be competitive and used in new sectors by 2026, when it envisages the local production of low-carbon fertilisers. Additionally, the reduction in the cost of green hydrogen would lead to its use in light-duty FCEVs from 2029 onwards.

The Moroccan strategy recognises that to start the export of hydrogen, additional investment will be necessary for infrastructure: pipelines and refuelling stations for green hydrogen, the adaptation of the existing Maghreb-Europe pipeline, as well as the extension and adaptation of the current port infrastructure.

Without the realisation of these achievements, policy makers cannot start the next phase of policy making. We can define these necessary steps as **chokepoints** for the hydrogen strategy application. It would be beneficial to recognise endogenous chokepoints and exogenous ones (Table 5).

Table 5 Examples of chokepoints

Endogenous chokepoints	Exogenous chokepoints
Internal factors within a country that can hinder the progress of its hydrogen strategy. They are specific to the country's own conditions, resources and capabilities.	External factors outside the control of the country, which can impact the success of its hydrogen strategy.
• Domestic infrastructure is not developed as foreseen. • Local demand remains low, lack of local commitment to consume hydrogen. • Lack of experienced players to up-scale hydrogen production to the next phase.	• CAPEX of electrolysers of renewable energy plants not reducing at the pace needed. • Lack of import/export infrastructure. • Lack of demand in importing countries. • Lack of supply from exporting countries. • Lack of manufacturing capacity. • Geopolitical issues affecting trade policies and technology transfer.

Understanding and addressing potential chokepoints facilitates policy making. It involves continuously re-assessing technological advancements, market responses and policy actions within the presented timetable. Recognising an emerging chokepoint also allows for re-assessing the policy actions needed to either maintain the hydrogen sector and avoid boom-and-burst dynamics, or to address the specific chokepoint.

9.3 Governance structure of the hydrogen sector

The concept of governance is understood here as a system of rules and roles that determine how decisions are made and implemented. It encompasses the processes by which authority is conferred on selected decision makers, by which they make the rules, and by which those rules are enforced and modified.

Understanding governance in the context of the hydrogen sector requires a comprehensive analysis of the various actors involved, their roles, and the processes by which they are selected and linked to the broader society. This includes policy makers, regulatory bodies, industry stakeholders and civil society organisations (see section 3). Different governance structures can lead to different outcomes in terms of co-ordination, efficiency and effectiveness of policies.

The hydrogen sector will require multiple activities from the public sector to be sustained (Table 6).

Table 6 Activities from the public sector

Category	Activity
Strategic management	Long-term target setting (strategy) Strategy application and monitoring
Policy making	Supporting policies definition Financial counterparty Finance facilitation Hydrogen definition
System operation	Management of public infrastructure Standards application and security code Monitoring Statistics collection and sharing
Trading relationship	Partner identification and liaison
End user regulation	Industrial development Industrial policies Green mandates Monitoring of mandates
Research	Research priorities setting R&D funding

Effective governance requires a clear delineation of roles and responsibilities among the key actors. Policy makers need to define the decision-making processes, identify the relevant stakeholders, and establish mechanisms for co-ordination and collaboration. Understanding who holds decision-making authority, how roles are defined and linked, and the level of co-ordination required is crucial for effective hydrogen sector development. It is possible to identify the main solutions for governance of the hydrogen sector.

Centralised governance

Appointing a governing body to oversee and govern activities related to green hydrogen ensures centralised decision making and accountability. By entrusting the responsibility to an established governing body, such as a ministry or agency with relevant expertise, there is a clear line of authority and accountability. This allows for efficient and streamlined decision-making processes, as decisions can be made promptly without the need for extensive co-ordination among multiple entities.

Appointing an existing governing body

An existing governing body *(e.g.* the energy authority) is likely to have established protocols, resources and infrastructure in place, which can facilitate the implementation and enforcement of policies related to green hydrogen. This reduces the need for creating new structures from scratch and can potentially save time and resources.

However, there are also some potential drawbacks to appointing an existing governing body. Depending on the composition and mandate of the governing body, certain stakeholders or perspectives may have been historically under-represented or overlooked in decision-making processes. This may increase the vulnerability to biases or conflicts of interest within that body.

In addition, it may lack the specific expertise needed for the hydrogen sector, and may rely on staff with adjacent experience.

Appointing a new governing body

Establishing a new governing body specifically dedicated to overseeing activities can allow for focused expertise and specialisation (Box 21). By creating a dedicated governing body, policy makers can bring together experts and stakeholders who possess in-depth knowledge and understanding of the specific challenges and opportunities related to green hydrogen. This specialised focus can lead to more informed and effective decision-making processes, as the governing body can develop tailored policies and strategies to drive the development of the green hydrogen sector.

However, establishing a new governing body also presents challenges. A main concern is the potential duplication of efforts and increased bureaucracy. Creating a new governing body requires administrative resources, funding, and infrastructure, which may divert resources from other important priorities. Additionally, co-ordination and co-operation with existing institutions and agencies may be necessary to avoid overlapping mandates and conflicting policies. The establishment of a new governing body can introduce additional complexities in terms of governance structures and decision-making processes. It may take time to establish effective mechanisms for collaboration and co-ordination among different entities, potentially slowing the implementation of green hydrogen policies.

Box 21 The centralised approach of Oman

Hydrogen Oman (Hydrom) was established in 2022 as a central and independent entity to lead Oman's green hydrogen sector. It operates under the directives of the Sultan and Prime Minister of Oman and is fully owned by Energy Development Oman (EDO) and regulated by the Ministry of Energy and Minerals. Hydrom's mission is to develop the green hydrogen sector in Oman by enabling the delivery of projects competitively and at scale for the world, with the vision of positioning the country as a leading global green hydrogen hub. Hydrom's primary functions are:

- **Master planning:** Hydrom is responsible for planning the green hydrogen sector in Oman.
- **Land allocation and auction management:** Hydrom manages the process for allocating government-owned land to green hydrogen projects. This includes handling the auction process for project allocation.
- **Infrastructure co-ordination:** The entity co-ordinates the common infrastructure necessary for the hydrogen sector and the connection of an ecosystem of industries.
- **Overseeing project execution:** Hydrom has the responsibility to oversee the execution of green hydrogen projects, ensuring that they align with Oman's energy goals.
- **Data management:** Hydrom manages a data repository on wind and solar resources, which are crucial for the development of renewable energy projects in the country.

Distributed governance

Alternatively, policy makers could foster the level of co-ordination needed using existing institutional arrangements (Box 22).

Distributed governance structures – such as inter-ministerial committees, inter-agency working groups, parliamentary committees, public-private partnerships, task forces and multi-stakeholder initiatives – could be backed by institutional agreement tools. Institutions and agencies in charge of territorial planning and water resources should be involved in such groups, as land and water will be impacted by the hydrogen sector development.

Box 22 The decentralised approach of India

India's Hydrogen Strategy, known as the Green Hydrogen Mission, envisions the use of a decentralised governance structure. An Empowered Group (EG), chaired by the Cabinet Secretary and featuring Secretaries of the Government of India alongside industry experts, will oversee strategic activities. The EG's responsibilities include providing guidance, undertaking continuous progress monitoring, recommending policy interventions to advance mission objectives and approving mid-course corrections when necessary.

Empowered Groups represent a form of inter-ministerial and inter-regional collaboration, a characteristic approach of the Indian government in addressing various socio-economic development issues. For instance, multiple EGs were established to combat the COVID-19 pandemic.

The Empowered Group for Green Hydrogen includes the principal scientific advisor to the Government of India, the chief executive officer of NITI Aayog (National Institution for Transforming India, a governmental public policy think tank), and Secretaries from different key ministries and departments.

This Empowered Group will ensure synergy between the Mission and other Government of India programmes related to hydrogen, fostering co-ordinated action among participating ministries/departments.

Beyond the Empowered Group, the Governance Framework includes a National Green Hydrogen Advisory Group, serving as the principal advisory body on science and technology matters, and supporting the Empowered Group. Chaired by the Principal Scientific Adviser to the Government, this Advisory Group comprises experts from academic and research institutions, industry and civil society. The Green Hydrogen Mission Secretariat, headquartered in the Ministry of New and Renewable Energy (the co-ordinating Ministry), is led by the Mission Director and comprises subject matter experts and professionals, overseeing day-to-day activities.

The strategy anticipates that various ministries/departments will implement green hydrogen projects in their respective sectors (including fertilisers, refining, natural gas, transport, shipping, steel, etc.) under the overarching guidance of the Empowered Group.

PART 4

Drafting guide

10. Drafting guide

The vast diversity of published national hydrogen strategies and roadmaps demonstrate a broad array of approaches in their development process. Policy makers in different countries operate under varying conditions, encompassing differences in national strategies, the potential for deployment of the hydrogen value chain, sets of priorities, key stakeholders, and initial opportunities for engaging in international green hydrogen and green product trade.

In such conditions, it may be challenging and unnecessary to create a standardised guide for developing hydrogen strategies. The idea of a standardised guide might initially seem appealing for its simplicity and directness. However, inherent challenges make this approach less feasible and effective.

Firstly, given the diverse economic, political, and environmental landscapes across different countries, a one-size-fits-all standardised guide could lead to strategies that are not optimally tailored to each nation's unique circumstances. Additionally, all authors brings their own set of experiences, expertise, and perspectives, which inevitably shape the content and recommendations of a guide. This could lead to a narrow focus, potentially overlooking critical aspects specific to certain regions or technologies. It also risks propagating the author's own preferences and viewpoints, which may not apply universally or be beneficial in diverse global contexts.

The risk of perpetuating prevalent economic structures is another significant concern when considering a standardised guide for developing hydrogen strategies. Such guides, often influenced by dominant global economic narratives, might inadvertently prioritise models that align with these existing structures. For example, they might overemphasise export-oriented approaches for developing countries, re-inforcing traditional economic roles rather than exploring innovative or self-sustaining models that are more suited and realistic to their specific needs.

Moreover, a standardised guide might inadvertently encourage homogenisation in strategy development. If countries rely too heavily on a standardised approach, they might end up adopting similar strategies, over-relying on similar sources and exploring the same technological pathways. This uniformity could stifle innovation and the exploration of novel, more suitable solutions for different countries.

A standardised guide may also quickly become outdated, failing to incorporate the latest technological advancements or shifts in global dynamics. The need for flexibility and adaptability in strategy development cannot be overstated – qualities that a rigid guide may struggle to provide.

10.1 Four passages

In summary, while a standardised guide for developing hydrogen strategies might offer clarity and direction, its potential drawbacks – including the risk of homogenisation, the influence of author bias and the inability to adequately address the unique needs of each country – suggest that a more nuanced and adaptable approach is required. However, four key drafting steps emerge as the most-found in published strategies and as crucial for formulating a long-term hydrogen policy (Figure 22).

Figure 22 Flowchart for hydrogen strategy making

Step 1. Setting the scene	◦ Securing political support ◦ Establishing a working group of stakeholders willing to participate in the strategy drafting ◦ Allocation of resources (human and time) ◦ Attracting international support (if needed) ◦ Capacity building
Step 2. National economy analysis	◦ Analysis of the energy, climate, and industrial strategy ◦ Analysis of the hydrogen production potential and backward linkages ◦ Analysis of local initiatives in the hydrogen sector: industry, R&D, education ◦ Analysis of potential end-use directions ◦ Positioning in international trade
Step 3. Modelling, strategic planning and policy formulation	◦ Priority setting along the value chain ◦ Scenario modelling ◦ Definition of long-term goals based on phase approach ◦ Barriers mitigation approach ◦ Policy measures
Step 4. Finalisation and making it real	◦ Definition of key steps and responsible stakeholders ◦ Governance structure ◦ Public discussion and approval of the final document by the governement ◦ Plan for regular updates of the document

Step 1: Setting the Scene

This first step is essential in establishing the foundation for developing a hydrogen strategy.

Firstly, political actions are crucial. This includes the commitment from government officials to initiate and back the development of the strategy, along with assembling a dedicated working group of authors. Such political backing ensures that the strategy development process is prioritised and receives the necessary attention and resources. This initial step is key in aligning governmental objectives with the strategic goals of hydrogen sector development.

Secondly, substantial resources will be required. The process of drafting the strategy (from the moment the task is assigned to the approval of the final document) can take from six months to 2-3 years, involving a team of several individuals. Some countries may leverage resources from ministries, agencies and national institutions engaged in techno-economic modelling; assemble a strategy development team from multiple organisations; and enlist the assistance of costly external consultants, while other countries are resource-constrained and compelled to seek help from international development agencies – such as IRENA, Germany's International Co-operation Agency (GIZ) and the US Agency for International Development (US AID)–and multilateral development banks.

An additional opportunity may involve tapping into the resources of national stakeholders, especially those related to the "Key players' segment of the stakeholders" matrix (see section 3). These are the stakeholders with more power and interest in developing a strategy, hence they may be willing to invest financial and human resources in such an endeavour. However, it is crucial for policy makers to maintain a balance of interests to avoid skewing towards the narrow interests of specific groups.

The working group involved in the strategy development process must obtain the necessary resources, data and political support. Key stakeholders are needed to deliver valuable input regarding expected production, demand, and export options, and under different scenarios. Capacity building through specialised educational programmes offered by international agencies can equip the team with the initial level of competencies required for developing a hydrogen strategy. It is particularly important to study the experience of developing hydrogen strategies in several countries with similar socio-economic and geopolitical parameters.

This step marks the beginning of the stakeholder engagement process, which will continue throughout the entire strategy development process and its subsequent implementation. Best practices, as demonstrated in section 3, highlight maximum coverage, regularity, and an iterative approach in discussing goals, tasks and individual elements of the strategy.

> "High-level political support is crucial, as the strategy drafting process involves numerous stakeholders. Without reliable political backing, there is a risk of ending up with multiple versions of the strategy."
>
> –Manuel El-Amine, Germany's Federal Ministry for Economic Affairs and Climate Protection

Step 2: National System Analysis

The second step is dedicated to a comprehensive analysis of national strategies in the areas of low-carbon development, energy, energy security, and industrial development, including LTES, as well as an aggregated assessment of the country's opportunities in the hydrogen value chain on the supply, transport and end use sides.

The primary task is to identify policy drivers for a hydrogen sector specific to the country. As shown in section 2, decarbonisation and industrial development are likely to be among these drivers, but each country may have unique features that can greatly shape the strategy development path. Long-term planning strategic documents (section 4) may contain quantitative benchmarks for the long-term hydrogen demand or assessments of resources required for its production. These data will form the basis for techno-economic modelling conducted in Step 3.

The assessment of green hydrogen production potential, as illustrated in section 4, can be conducted at four levels (from resource to market potential) using research of varying depth and detail. The simplest approach is to use the results of "top-down" potential studies (such as the HYPAT project[8]) and atlases developed based on GIS data (like the Global PtX Atlas by Fraunhofer IEE[9]). A more complex and resource-intensive path includes intra-country analysis, including the status of market and technological infrastructure, land allocation procedures and overall trends in the development of the energy sector.

Analysing potential end use directions for hydrogen can provide a more in-depth knowledge on the actual amount needed in the future. Evaluating the current total consumption of grey hydrogen and key consumers (making sure that hydrogen developments are tracked by national statistics) (IRENA, 2024c) will thus provide the foundation for forming scenarios of hydrogen demand growth by 2030-2050. Taking into account possible net-zero targets and policy measures to achieve these, additional demand can be considered for both green industrialisation and decarbonisation of other hard-to-abate sectors that are currently not yet using green hydrogen.

The balance between hydrogen production potential and end use, logistical infrastructure, and the country's geographic location concerning trade routes defines the possible role that the country can play in future international hydrogen trade – including roles as an exporter, importer, self-sufficient entity and hub (see section 6).

Finally, at this step, the evaluation of hydrogen initiatives in the country, such as R&D, education, raw material production, components, and equipment for the hydrogen value chain, can be crucial. The additional value of analysing these factors within the strategy development framework is that it reduces costs for potential investors and enhances their confidence in the development of the hydrogen sector in the country – as the hydrogen strategy becomes a public source of valuable information.

"Countries must possess a foundational set of resources and technological expertise to initiate the development of the hydrogen sector. Additionally, they should prioritise the development of indigenous technologies alongside the acquisition of technologies from more advanced nations. This approach is crucial to ensure that countries can maximise the economic benefits derived from their investments."

–Dr. Mohd Nor Azman Bin Hassan, Malaysia's Ministry of Science, Technology and Innovation

Step 3: Modelling, Strategic Planning and Policy Formulation

If the previous step focused on analysing the status quo of the energy and hydrogen sectors and existing strategic plans in the country, with a predominance of qualitative assessment, Step 3 can commence with techno-economic modelling of potential scenarios with their quantitative evaluation.

8 See https://hypat.de/hypat-en.

9 See https://maps.iee.fraunhofer.de/ptx-atlas.

Such modelling will require additional resources but will create a more reliable foundation for priority setting and subsequent policy development by filtering out less promising pathways. As demonstrated in section 4, modelling tools provide the interconnection of technological and economic parameters across multiple economic sectors, offering more reliable answers to critical questions facing investors. A detailed strategic analysis of options will later help determine the financial indicators and economic justification for the proposed policy measures.

Stakeholder engagement and LTES lay the groundwork for the critical considerations in the development of priority settings (section 4). Stakeholder engagement ensures that the development of hydrogen policies is informed by a comprehensive understanding of the interests, concerns and capabilities of all relevant parties. The use of LTES and alignment with national objectives ensure coherence, efficiency and effectiveness in policy implementation. Together, these sections of the report provide a strategic approach to priority setting within the hydrogen value chain. This involves determining which production pathways, transport systems, and end use applications to target first, informed by a careful evaluation of technological readiness, economic considerations and the potential for decarbonisation across different sectors.

Following the prioritisation phase, the next critical step in developing a green hydrogen strategy is the setting of precise and informed targets (section 7). To establish such targets effectively, considerations must encompass the renewable energy potential, the current and projected demand for hydrogen, existing infrastructure, and the most relevant assessments of the technical and economic feasibility of hydrogen technologies available at the time of writing the strategy (given the rapid development of hydrogen technologies and uncertainties about their technological efficiency and economies of scale).

The third step continues with the identification of key risks and the development of measures to mitigate them (see section 7). The selection of priorities, targets and barriers are interrelated and require an in-depth analysis of the specific characteristics of each country. The more thorough this work, the greater the number of "low-hanging fruits" and, conversely, of less promising directions that can be discovered, optimising policy measures in optimal directions.

Policy support measures can now be elaborated and presented for the hydrogen sector, as discussed in section 9 and well-explored in numerous IRENA publications (Table 4). The set of support measures will be determined by the specific opportunities and features of each country. Best practices in developing hydrogen strategies involve discussing this matter with key stakeholders.

As depicted in section 9, strategic planning is typically conducted using a phased approach, delineating phases such as technology readiness, market penetration and market growth. Milestones for these phases are recommended to be selected based on the results of scenario modelling, current forecasts of hydrogen technology cost reduction and the unfolding global market.

"Techno-economic analysis is highly crucial. Invest the effort to comprehend demand and opportunities. It's challenging and time-consuming (6-12 months), but truly worthwhile for basing your strategy on quantitative assessments. With such analysis, you free yourself from developing unnecessary additional policy measures, especially in the initial stages."

—Jazaer Dawody, Swedish Energy Agency

Step 4: Finalisation and "Making It Real"

After key goals, phases, and milestones are defined; barriers are identified; priorities are set; targets are presented; and primary policy measures are elaborated, one can proceed to create the most specific (as much as possible) implementation measures, in collaboration and co-ordination with the responsible stakeholders. This may not always be practical for later phases of the strategy, but it is crucial for the initial phase because governance, standards, and regulation are typically developed at this stage, requiring significant involvement from policy makers.

The selection and approval of the governance structure are crucial for implementing the strategy. Different types of this structure (centralised, decentralised or hybrid), as shown in section 9, have various advantages and disadvantages. The choice of the structure may be influenced by the characteristics of strategic management in the country, but the simpler and more specific it is in terms of responsibility and resource allocation, the better.

Final drafts of hydrogen strategies usually undergo a stakeholder discussion procedure, not only with key players but also with other stakeholders from the stakeholder matrix (*e.g.* public organisations). This process typically takes several weeks or months but ultimately results in a more balanced document.

As demonstrated by the practices of pioneering countries, hydrogen strategies need to be updated regularly (every 3-5 years), assessing the status of achieving previously set priorities and the relevance of earlier identified priorities.

"It is crucial to provide a clear indication of the timeline and funds for the instruments intended to be used in the strategy. A transparent governmental structure with defined obligations for involving stakeholders is a key solution."

—Florian Marko, ex-Federal Ministry for Economic and Digital Affairs (2021-2022), ex-Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (2018-2021), Austria

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Annex

Table A.1 Targets of selected national hydrogen strategies and roadmaps

	Production (Mt)	**Consumption (Mt)**	**Electrolysis capacity (GW)**	**Hydrogen-related renewables capacity (GW)**
Argentina	0.3 (2030) 2 (2040) 5 (2050)	0.02 (2030) 0.5 (2040) 1 (2050)	30 (2050)	55 (2050)
Australia	1 (2030) 18 (2050)	0.5 (2019)		
Austria			1 (2030)	
Belgium			0.15 (2026)	
Bulgaria		0.2 (2022)		
Canada		3 (2025) 4 (2030) 20 (2050)		
Chile	0.2 (2025)		5 (2025)	5-8 (2025) 300 (2050)
China	0.1-0.2 (2025)			
Colombia		1.85 (2030)	1-3 (2030)	1.5-4 (2030)
Costa Rica		0.02 (2030) 0.42 (2050)	0.2-1 (2030)	
Croatia		0.0053-0.05 (2030) 0.214-0.266 (2050)	0.07 (2030) 2.75 (2050)	
Czech Republic	0.101 (2030) 0.284 (2040)			
Denmark			4-6 (2030)	

Ecuador			1 (2030)	2 (2030)
EU	10 (2030)			
France			6.5 GW (2030)	
Germany		2.87-3.9 (2030)	10 (2030)	
Croatia		0.0053-0.05 (2030) 0.214-0.266 (2050)	0.07 (2030) 2.75 (2050)	
Hungary	0.036 (2030)	0.024 (2030)	0.24 (2030)	
India	5 (2030)			125 (2030)
Ireland				2 GW offshore wind (2030)
Italy			1 (2026) 5 GW (2030)	
Japan		3 (2030) 12 (2040) 20 (2050)	15 (2030)	
Kenya			0.1 (2027) 0.25 (2032)	0.15 (2027), 0.45 (2032)
Republic of Korea		5.26 (2040)		
Luxembourg		0.125-0.3 (2050)		
Malysia	3.06 (2040) 7.4(2050)	1 (2030) 4.6 (2040) 10.33 (2050)		
Morocco	0.42-0.9 (2030) 2.04-3.98 (2040) 4.62-9.21 (2050)	0.11-0.25 (2030) 0.66-1.23 (2040) 1.18-2.33 (2050)	2.8-5.2 (2030) 13.9-23.0 (2040) 31.4-52.8 (2050)	1.6-3.4 (2030) 7-9.9 (2040) 10.3-10.7 (2050)
Namibia	1-2 (2030) 5-7 (2040) 10-15 (2050)			
Netherlands	0.6 (2030)	0.48- 1.114 (2030)	6-8 (2030)	
Oman	1-1.5 (2030) 3.25-3.75 (2040) 7.5-8.5 (2050)		8-15 (2030) 35-40(2040) 95-100 (2050)	16-30 (2030) 65-75 (2040) 175-185 (2050)

Panama	0.5 (2030) 2 (2040)			
Poland		1.3 (2020)	2 (2030)	
Portugal			2-2.5 (2030)	
Slovak Republic		0.2 (2030); 0.4-0.6 (2050)		
South Africa	0.5 (2030)	1.4 (2050)	15 (2040)	
Spain			0.3-0.6 (2024) 4 GW (2030)	
Sweden			5 (2030) 15 (2045)	
Trinidad and Tobago	4 (2065)	1.5 (2065)	25 (2065)	57 (2065) Offshore wind
Tunisia	0.32 (2030) 2.1 (2040) 8.3 (2050)		3.85 (2030) 23.3 (2040) 86.8 (2050)	5 (2030) 28.4 (2040) 100 (2050)
Türkiye			2 (2030) 5 (2035) 70 (2053)	
United Arab Emirates	3.375 (2040) 7.07 (2050)		55.12 (2040) 83.2 (2050)	97.28 (2040) 208.3 (2050)
United Kingdom			1 (2025) 5 (2030)	40 (2030) offshore wind
United States	10 (2030), 20 (2040), 50 (2050)			
Uruguay	1 (2040)		0.150-0.350 (2025) 1-2 (2030), 10 (2030)	20 (2040)
Viet Nam	0.1-0.5 (2030) 10-20 (2050)			

Note: targets are streamlined in Mt of green hydrogen and GW.

Table A.2 Policies of national hydrogen strategies and roadmap, selected countries

	Direct financial support for electrolysers	Production support mechanism	Mobilisation of finance	Hydrogen infrastructure planning and support	Demand-side support	Regulation, standards and certification	Land permits	Skill policies	Local content manufacturing	Knowledge creation
Argentina		+	+	+		+		+	+	+
Australia				++		++		++	++	++
Austria	+	+		+	+	+				
Belgium	++		++	++	+			++		++
Bulgaria	+	+	+	+	+	++		++		+
Canada			+			+		+		+
Chile			++			++	++	++		++
China		+	+			+		+		
Colombia		++	++	++	++	++		++	++	++
Costa Rica		++	++	++	++	++		++		++
Croatia			+			+		+		+
Czech Republic						+		+		
Denmark		++	+	+		+				+
EU	++	++	++	++	+	++				+
France	++			++	++			++		++
Germany	++	++	++	++	++	++	++	++	++	++
Hungary		+		+	+	+				+
India	++	++		++	++	++		++		
Ireland			+	+	+	++		++		++
Italy	+				+	+		+	+	

Japan	++	+	++	+	+	++		+	+	++
Kenya			+							
Republic of Korea				+		++				++
Luxembourg			+		+			+		+
Morocco			+	+	+	+				
Namibia			+	+		+	+	+	+	
Netherlands		++		++		++				++
New Zealand										
Norway	++	++		+	+	+				+
Oman				+			++			
Panama			++	+	++	++		++		++
Paraguay										
Poland			+	+		++		+		+
Portugal		+	++	+	++	++		+		+
Singapore				+			+	+		+
Slovak Republic			+	++	+	++		+		+
South Africa		+	+	+	+	+		++	++	++
Spain		+		+	+	+		+		+
Sweden	++		++	++		++		++		++
Trinidad and Tobago							+	+	+	
Türkiye		+				+		+	+	
United Kingdom	++	++		++	++	++		++		++
United States	++	++		++					++	
Uruguay		+		+				+		

++ = policy described in detail, + = policy mentioned

Table A.3 Shades of hydrogen supported in national hydrogen strategies and roadmap

Green	Nuclear	Blue	Turquoise	Bio hydrogen
All	Argentina Canada China Czech Republic France Poland Slovak Republic Türkiye United Arab Emirates United Kingdom United States	Argentina Australia Belgium Canada Colombia Croatia Czech Republic Germany Hungary Indonesia Italy Japan Malaysia Netherlands Poland Republic of Korea Slovak Republic South Africa Trinidad and Tobago Türkiye United Arab Emirates United Kingdom United States Viet Nam	Belgium Czech Republic Germany South Africa Türkiye	Austria Canada Germany United States

Table A.4 End-use priorities in national hydrogen strategies and roadmap, selected countries

	Petrochemicals	Steelmaking	Long-haul aviation	Long-haul shipping	Long-haul trucks	Trains	Buses	FCEV cars	Power	Heating
Argentina	2	2	2	2	1	1	0	0	0	0
Australia	2	1	0	1	2	1	0	0	1	1
Austria	2	2	2	2	1	0	1	0	2	0
Belgium	2	1	2	2	2	1	0	1	1	1
Bulgaria	2	1	0	0	1	0	2	1	1	0
Canada	2	1	1	2	2	2	2	2	1	2
Chile	2	0	0	0	1	0	2	0	0	0
China	2	0	1	1	0	0	0	2	0	0
Colombia	2	1	0	0	2	0	2	2	1	1
Costa Rica	1	1	0	0	2	0	2	1	0	0
Croatia	2	1	1	1	0	1	1	1	0	0
Czech Republic	2	2	0	0	2	0	2	0	0	0
Denmark	2	0	2	2	1	0	1	1	0	0
EU	2	2	2	2	2	1	1	0	2	0
France	2	0	1	1	2	2	2	0	0	0
Germany	2	2	2	2	2	1	1	1	2	1
Hungary	2	1	0	0	1	0	1	2	0	0
India	2	2	0	2	2	0	2	0	0	0
Ireland	1	0	1	1	2	1	2	0	1	0
Italy	2	2	1	1	2	1	1	0	1	1
Japan	2	2	1	2	2	2	2	1	2	2

Kenya	2	0	0	0	1	0	0	0	1	0
Luxembourg	0	0	1	0	1	0	1	0	0	0
Morocco	2	0	1	1	1	1	1	0	1	1
Namibia	2	2	0	0	0	0	0	0	0	0
Netherlands	2	2	1	1	1	0	0	1	1	1
New Zealand	2	2	2	2	2	2	2	2	0	0
Norway	2	2	1	2	2	1	0	2	1	0
Oman	1	0	0	0	0	0	0	0	0	0
Panama	1	0	2	2	2	0	0	0	0	0
Paraguay	0	0	1	1	1	0	0	0	0	0
Poland	1	0	0	1	1	1	1	0	1	1
Portugal	1	1	0	1	1	1	1	0	1	1
Republic of Korea	0	0	0	0	0	1	2	2	2	2
Slovak Republic	1	1	1	0	1	1	1	0	0	0
South Africa	0	2	2	2	2	2	2	2	1	1
Spain	1	1	1	1	1	1	0	1	0	0
Sweden	2	2	1	1	1	0	0	0	0	0
Trinidad and Tobago	2	2	0	1	1	0	1	0	0	0
Türkiye	2	2	1	1	1	0	0	0	0	0
United Kingdom	2	2	2	2	2	2	2	0	2	2
United States	2	2	2	2	2	0	2	1	2	1
Uruguay	1	0	0	1	2	0	1	1	0	0

2 = high priority, 1 = low priority, 0 = no priority/mentioning

Table A.5 Full list of currently available hydrogen strategies

Date	Country	Title	Link
Dec-17	Japan	水素基本戦略(Basic Hydrogen Strategy)	www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/20230606_report.html
Jan-19	Republic of Korea	수소경제 활성화 로드맵 (Hydrogen Economy Activation Roadmap)	https://policy.nl.go.kr/search/searchDetail.do?rec_key=SH2_PLC20190231080
Sep-19	New Zealand	A vision for hydrogen in New Zealand: Green paper	https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/hydrogen-in-new-zealand/a-vision-for-hydrogen-in-new-zealand
Nov-19	Australia	Australia's National Hydrogen Strategy	www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy
Jun-20	Norway	The Norwegian Government's hydrogen strategy	www.regjeringen.no/en/dokumenter/the-norwegian-governments-hydrogen-strategy/id2704860/
Jul-20	European Union	A hydrogen strategy for a climate-neutral Europe	https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en
Aug-20	Portugal	Estratégia Nacional de Hidrogénio (EN-H2) (National Hydrogen Strategy (EN-H2))	www.dgeg.gov.pt/pt/areas-transversais/relacoes-internacionais/politica-energetica/estrategia-nacional-para-o-hidrogenio-en-h2/
Oct-20	Spain	Hoja de Ruta del Hidrógeno (Hydrogen Roadmap)	www.miteco.gob.es/es/ministerio/planes-estrategias/hidrogeno.html
Nov-20	Chile	National Green Hydrogen Strategy	https://energia.gob.cl/noticias/nacional/gobierno-presenta-la-estrategia-nacional-para-que-chile-sea-lider-mundial-en-hidrogeno-verde
Nov-20	Italy	Strategia Nazionale Idrogeno Linee Guida Preliminari (National Hydrogen Strategy Preliminary Guidelines)	www.mimit.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf
Dec-20	Canada	Hydrogen Strategy for Canada	https://natural-resources.canada.ca/climate-change/canadas-green-future/the-hydrogen-strategy/23080
Dec-20	France	Stratégie nationale pour le développement de l'hydrogène décarboné en France (National Strategy for the Development of Decarbonised Hydrogen in France)	www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-renewable-hydrogen-in-France.pdf

Jan-21	Morocco	Feuille de Route de l'Hydrogène Vert (Green Hydrogen Roadmap)	https://www.mem.gov.ma/Lists/Lst_rapports/Attachments/36/Feuille%20de%20route%20de%20hydrog%C3%A8ne%20vert.pdf
Jun-21	Paraguay	Hacia la ruta del Hidrogeno Verde en Paraguay (Towards the Green Hydrogen Route in Paraguay)	www.ssme.gov.py/vmme/index.php?option=com_content&view=article&id=2064&Itemid=552
Jun-21	Slovak Republic	Národná vodíková stratégia Pripravení na budúcnosť (National Hydrogen Strategy Ready for the Future)	www.enviroportal.sk/energetika/dokumenty/narodna-vodikova-strategia-pripraveni-na-buducnost-2021
Jun-21	Hungary	Magyarország Nemzeti Hidrogénstratégiája (Hungary's National Hydrogen Strategy)	https://cdn.kormany.hu/uploads/document/a/a2/a2ba2b2b7ed5179b17694659b8f050ba9648e75a0bf.pdf
Jul-21	Czech Republic	The Czech Republic's Hydrogen Strategy	https://danovky.cz/en/news/detail/893
Aug-21	United Kingdom	UK hydrogen strategy	www.gov.uk/government/publications/uk-hydrogen-strategy
Sep-21	Luxembourg	Stratégie hydrogène du Luxembourg (Luxembourg's Hydrogen Strategy)	https://gouvernement.lu/fr/actualites/toutes_actualites/communiques/2021/09-septembre/27-turmes-hydrogene.html
Oct-21	Colombia	Hoja de Ruta del Hidrógeno en Colombia (Hydrogen Roadmap in Colombia)	minenergia.gov.co/es/micrositios/enlace-ruta-hidrogeno/
Oct-21	Poland	Polska Strategia Wodorowa do roku 2030 (Polish Hydrogen Strategy until 2030)	gov.pl/web/klimat/polska-strategia-wodorowa-do-roku-2030
Oct-21	South Africa	Hydrogen Society Roadmap for South Africa 2021	https://dst.gov.za/index.php/resource-center/reports/strategies-and-reports/3574
Nov-21	Sweden	Förslag till Sveriges nationella strategi för vätgas, elektrobränslen och ammoniak (Proposal for Sweden's National Strategy for Hydrogen, Electrofuels and Ammonia)	www.energimyndigheten.se/nyhetsarkiv/2021/forslag-till-nationell-strategi-for-fossilfri-vatgas/
Dec-21	Denmark	The government strategy for power-to-X	https://ens.dk/en/our-responsibilities/power-x

Mar-22	Croatia	Hrvatsku Strategiju (Croatian Strategy)	https://narodne-novine.nn.hr/clanci/sluzbeni/2022_03_40_492.html
Mar-22	China	氢能产业发展中长期规划(2021-2035年)(Medium and Long-term Plan for Hydrogen Energy Industry Development (2021-2035))	www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html
Jun-22	Austria	Wasserstoffstrategie für Österreich (Hydrogen Strategy for Austria)	www.bmk.gv.at/themen/energie/energieversorgung/wasserstoff/strategie.html
Jul-22	Uruguay	Green Hydrogen Roadmap in Uruguay	www.gub.uy/ministerio-industria-energia-mineria/comunicacion/noticias/green-hydrogen-roadmap-in-uruguay
Sep-22	Costa Rica	Estrategia Nacional de Hidrógeno verde de Costa Rica (Costa Rica's National Green Hydrogen Strategy)	https://cicr.com/noticias_pt/consulta-sobre-la-estrategia-nacional-y-plan-de-accion-del-hidrogeno-verde-en-costa-rica/
Oct-22	Belgium	Vision and strategy Hydrogen	https://economie.fgov.be/en/themes/energy/sources-and-carriers-energy/hydrogen/belgian-federal-hydrogen
Oct-22	Oman	Green Hydrogen in Oman	https://hydrom.om/events/hydromlaunch/221023_MEM_En.pdf
Oct-22	Singapore	Singapore's National Hydrogen Strategy	www.mti.gov.sg/Industries/Hydrogen
Nov-22	Namibia	Namibia Green Hydrogen and Derivatives Strategy	https://allafrica.com/view/resource/main/main/id/00130863.html
Nov-22	Netherlands	Hydrogen Roadmap for the Netherlands	https://nationaalwaterstofprogramma.nl/
Nov-22	Trinidad and Tobago	The roadmap for a green hydrogen economy in Trinidad and Tobago	http://dx.doi.org/10.18235/0004555
Jan-23	India	National Green Hydrogen Mission	https://mnre.gov.in/national-green-hydrogen-mission/
Mar-23	Estonia	Estonian Hydrogen Roadmap	https://kliimaministeerium.ee/en/hydrogen
Mar-23	Finland	Government resolution on hydrogen	https://julkaisut.valtioneuvosto.fi/handle/10024/164746
Apr-23	Panama	Estrategia Nacional de Hidrógeno Verde y Derivados de Panamá (National Strategy for Green Hydrogen and Derivatives of Panama)	www.gacetaoficial.gob.pa/pdfTemp/29771_B/98196.pdf

Apr-23	Türkiye	Türkiye Hidrojen Teknolojileri Stratejisi ve Yol Haritası (Turkey's Hydrogen Technologies Strategy and Roadmap)	https://enerji.gov.tr/announcements-detail?id=20349
May-23	Bulgaria	ВОДОРОДНО БЪДЕЩЕ ЗА БЪЛГАРИЯ (Hydrogen-based future for Bulgaria)	strategy.bg/StrategicDocuments/View.aspx?lang=bg-BG&Id=1624
Jun-23	Japan (update)	水素基本戦略（Basic Hydrogen Strategy） - Update	www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/20230606_report.html
Jun-23	United States	U.S. National Clean Hydrogen Strategy and Roadmap	www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html
Jul-23	Ecuador	la Hoja de Ruta y la Estrategia para la Producción de Hidrógeno Verde (the Roadmap and Strategy for the Production of Green Hydrogen)	www.recursosyenergia.gob.ec/ecuador-presento-la-hoja-de-ruta-y-la-estrategia-para-la-produccion-de-hidrogeno-verde/
Jul-23	Germany	Die Nationale Wasserstoffstrategie (The National Hydrogen Strategy)	www.bmwk.de/Redaktion/DE/Wasserstoff/Dossiers/wasserstoffstrategie.html
Jul-23	Ireland	National Hydrogen Strategy	www.gov.ie/en/publication/624ab-national-hydrogen-strategy
Jul-23	United Arab Emirates	National Hydrogen Strategy	https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/environment-and-energy/national-hydrogen-strategy
Aug-23	New Zealand (update)	New Zealand's hydrogen roadmap	www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-strategies-for-new-zealand/hydrogen-in-new-zealand/roadmap-for-hydrogen-in-new-zealand
Aug-23	Sri Lanka	Sri Lanka's Green Hydrogen Roadmap	https://greenstat.no/en/news/greenstat-celebrates-sri-lanka-s-ambitious-green-hydrogen-roadmap
Sep-23	Algeria	Stratégie Nationale de Développement de l'Hydrogène en Algérie (National Hydrogen Development Strategy in Algeria)	www.energy.gov.dz/?article=stratgie-nationale-de-dveloppement-de-l-hydrogne-en-algrie-4
Sep-23	Argentina	Estrategia Nacional para el Desarrollo de la Economía del Hidrógeno (National Strategy for the Development of the Hydrogen Economy)	www.argentina.gob.ar/asuntos-estrategicos/estrategia-nacional-para-el-desarrollo-de-la-economia-del-hidrogeno-0
Sep-23	Kenya	The Green Hydrogen Strategy and Roadmap for Kenya	www.eeas.europa.eu/delegations/kenya/green-hydrogen-strategy-and-road-map-kenya_en

Oct-23	Germany (update)	The 2023 National Hydrogen Strategy	www.bmwk-energiewende.de/EWD/Redaktion/EN/Newsletter/2023/08/Meldung/direkt-finds.html
Oct-23	Malaysia	Hydrogen Economy & Technology Roadmap	www.mosti.gov.my/en/dasar/
Dec-23	France (Update)	Stratégie nationale pour le développement de l'hydrogène décarboné en France (décembre 2023) (National Strategy for the Development of Decarbonized Hydrogen in France (December 2023))	www.ecologie.gouv.fr/consultation-sur-nouvelle-strategie-francaise-deploiement-lhydrogene-decarbone#:~:text=Un%20Conseil%20national%20de%20l,de%2010%20GW%20en%202035.
Dec-23	Indonesia	Strategi Hidrogen Nasional (National Hydrogen Strategy)	https://ebtke.esdm.go.id/post/2023/12/15/3680/strategi.hidrogen.nasional
Feb-24	Viet Nam	PHÊ DUYỆT CHIẾN LƯỢC PHÁT TRIỂN NĂNG LƯỢNG HYDROGEN CỦA VIỆT NAM ĐẾN NĂM 2030, TẦM NHÌN ĐẾN NĂM 2050 (Approval of the Strategy for Development of Hydrogen Energy in Vietnam until 2030, Vision to 2050)	https://thuvienphapluat.vn/van-ban/Tai-nguyen-Moi-truongQuyet-dinh-165-QD-TTg-2024-Chienluoc-phat-trien-nang-luong-hydrogen Viet-Nam-den-2030-tam-nhin-2050-598438.aspx
May-24	Oman (update)	Oman Green Hydrogen Strategy	https://hydrom.om
May-24	Tunisia	La Stratégie Nationale pour le développement de l'Hydrogène Vert et de ses produits dérivés [The National Strategy for the development of green hydrogen and its derivastives]	https://www.energiemines.gov.tn/fr/tc/actualites/news/la-strategie-nationale-pour-le-developpement-de-lhydrogene-vert-et-de-ses-produits-derives/?tx_news_pi1%5Bcontroller%5D=News&tx_newspi1%5Baction%5D=detail&cHash=684118a875b0c1e4426e186fa559d58a

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