National hydrogen strategies in a global context: common design elements across country specific visions

WORKING PAPER

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Abstract: Many countries around the world have recognised the importance of a hydrogen economy in reducing emissions and limiting the global temperature rise. Recently published national hydrogen strategies from countries across the globe inform how governments plan to support the hydrogen transition, highlight country-specific areas of interest, identify regulatory barriers and market opportunities and provide a country-specific context for the transition. By design, these hydrogen strategies present a national perspective on the emergence of a hydrogen economy over the upcoming decades. What is missing, though, is publicly available research on how the structure and content of national hydrogen strategies compare. Our work aims to address this gap by studying the structure of twelve national strategies published by countries from all continents and identifying common design elements and trends in a global context. Based on our findings, we highlight how hydrogen shall be produced, which applications will consume hydrogen, how demand will be met by supply and which policies shall support the build-up of a hydrogen economy. Our findings can help to better evaluate the implications of the transition towards a hydrogen economy in a global context.

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1. Introduction:

Fossil energy demand continues dominating our energy mix, being the main driver for human-made climate change. In response to the scientifically proven negative impact of human activity on the environment, nations signed the Paris Agreement in 2015 and have been joined by 192 countries to date. The agreement's main objective is to limit the global temperature increase to 2 °C while pursuing efforts to limit it to 1.5 °C. To meet this objective, profound changes to our energy model are needed. Renewable electricity generation will play a key role in this transition.

Renewable-based electrification is the most cost-effective approach to achieving climate neutrality. This means converting most energy use in industry and transport from fossil fuels to electricity generated by renewable energy sources. Direct electrification is possible in many sectors such as power generation, light transport, rail and others, and these should be the first areas to decarbonise by 2030. However, electrification has many technical and economic limitations in the so-called "hard-to-abate" sectors, which include heavy road transport, shipping, air transport and heavy industry (cement, steel and chemicals). Hydrogen is essential to move towards complete decarbonization of the economy, acting as an energy vector for renewable electricity to reach all these hard-to-abate sectors.

Many countries around the world have recognised the role of hydrogen in reducing emissions. By September 2021, twelve countries had already published national hydrogen strategies, and another 60 countries were actively exploring the role of hydrogen in their future energy system [1]. These national strategies inform how governments plan to support the hydrogen transition, highlight country-specific areas of interest, identify regulatory barriers and market opportunities and provide a country-specific context for the transition. Japan was the first country to publish its hydrogen strategy in 2017. In the following, France (2018) and Germany (2020) were the first countries with national strategies in place in Europe, while the EU published its own strategy shortly after.[1]

Several publications have analysed different national hydrogen strategies. A detailed study about the elements of national roadmaps and strategies[2] was published by the World Energy Council (WEC) in 2020 [2]. However, since most strategies have been published afterwards, the original WEC report is only based on a small sample of national strategies. A brief update was published in 2021 [1]. The International Energy Agency (IEA) closely monitors the emergence of a hydrogen economy in various reports. While national strategies are an important source in IEA reports, their analysis in the global [3] and regional context, for example, Latin America [3], is primarily based on their own industry and government consultations, modelling assumptions and research work. Private sector publications from consultancy companies, such as Paris based Yélé [4], provide a comprehensive overview of target setting across the different national strategies without in-depth analysis. National strategies from different counties are also used for analysing specific geopolitical and geo-economics questions, such as the role of hydrogen in the Mediterranean region [5].

What is missing, though, is publicly available research on how the structure and content of national hydrogen strategies compare. Our work aims to address this gap by studying the structure of these strategies and identifying common design elements and trends in a global

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[1] See, COM(2020) 301 final

[2] Our understanding is that the terms roadmap and strategy are often used interchangeably in this context. In the following, we refer to “strategies” when referring to national hydrogen roadmaps or strategies.

context. Following a systematic approach presented in Section 2, we review a sample of twelve national strategies from different countries on all five continents, comparing how, according to these national strategies, hydrogen shall be produced (Section 3), which applications will consume hydrogen (Section 3.2), how demand will be met by supply (Section 3.3) and which support policies shall support the build-up of a hydrogen economy (Section 3.4). Based on our findings, we highlight common elements across country-specific national hydrogen strategies (section 4) and show how our analysis can help scholars, policymakers and the industry to understand the context of different national strategies better and evaluate the implications of the transition towards a hydrogen economy.

2. Methodology:

Different national hydrogen strategies have common elements that describe how the role of hydrogen within the economy can evolve from being a feedstock for some industrial applications to an essential pillar of the energy system. The analysis followed is based on these four guiding questions, which all strategies address in a different way.

1.) **How** shall hydrogen be **produced** on a national level?
2.) **Which** applications and sectors are set to **consume** it?
3.) **How** would **demand** be met with **supply**?
4.) **What policies** are required to support the process?

The following analysis focuses on the different answers provided by national hydrogen strategies to these four leading questions. In section 3, we approach each of these questions in the same way. First, we summarise the latest scientific and non-scientific findings concerning production technologies, potential applications, long-distance transport options, and policies.

In a second step, we contrast these findings with the answers to these four questions provided by the latest national strategies published by twelve different countries between 2019 and early 2022 (Table 1). The review of all strategies published to date is beyond the scope and purpose of this study, which is intended to compare a representative sample in the international context to identify common elements. In total, twelve hydrogen roadmaps were chosen, covering the major European economies and the most important countries in each continent that had published their strategy by early 2022.

Most publications describe the emergence of a hydrogen economy until 2050, with intermediate targets specified for 2030 or 2040. South Korea (2040) and France (2028), with a shorter time horizon, are the exception. South Africa also specifies targets for intermediate years, which have been disregarded to ease comparison to other national strategies. Strategies also differ significantly in their complexity. The South Korean document is the shortest of all reviewed publications (16 pages), whereas the very detailed Canadian document has a length of 141 pages.

When analysing these documents, only explicit mentions were considered. For example, a strategy may open a door for pink hydrogen or blending. However, if not clearly stated and subject to the interpretation of the reader, pink hydrogen or blending would not be considered part of the strategy.

Only the information stated within the national strategies was considered without further studying other public reports or changes in the ongoing national debates. In addition, only strategies published by governmental agencies were included in this review. Consequently, the United States roadmap to a hydrogen economy, a joint document by various private actors and non-governmental organisations [6], has not been part of this review. China is the biggest producer and consumer of hydrogen to date and published a national hydrogen industry development plan in March 2022 [7]. This document mainly covers the evolution of hydrogen production prices and the support for research and pilot projects. However, the development plan misses several central elements of a national strategy and does not include a vision of the future role of hydrogen in the country. Therefore, it was decided not to include it in this study. After China, the United States is the second-biggest hydrogen consumer to date. Hence, the absence of the United States and Chinese perspectives is a major limitation of our work.

National strategies have very different formats. More concise strategies, like the Chilean document, have a presentation format. Elaborate strategies encompass detailed reports with more than one hundred pages (for example, Canada, South Africa and Australia). Shorter documents, such as the French, South Korean or Japanese strategies, tend to focus on specific measures, such as support policies or technology promotion.

Table 1: Reviewed hydrogen strategies

Country	Published	Horizon	Publisher	
Australia	November, 2019	2030-2050	Department of Industry, Innovation and Science	[8]
Canada	December,2020	2030-2050	Ministry of Natural Resources	[9]
Chile	November, 2020	2030	Ministry of Energy	[10]
Colombia	September,2021	2030-2050	Ministry of Mines and Energy	[11]
France	June, 2018	2028	Ministry for Ecological and Inclusive Transition	[12]
Germany	June 2020	2030-2050	Federal Ministry for Economic Affairs and Energy	[13]
Japan	March 2019	2030-2050	Ministerial Council on Renewable Energy, Hydrogen and Related Issues	[14]
Morocco	November, 2021	2030-2050	Ministry of Energy, Mines and Environment	[15]
South Africa	February, 2022	2024-2030-2040-2050	Department of Science and Innovation	[16]
South Korea	January, 2019	2040	Department of Energy New Industry, Ministry of Trade, Industry and Energy	[17]
Spain	October,2020	2030-2050	Ministry for the Ecological Transition and the Demographic Challenge	[18]
United Kingdom	August,2021	2030-2050	Secretary of State for Business, Energy & Industrial Strategy	[19]

3. Analysis: common elements of hydrogen strategies

National hydrogen strategies represent country-specific visions. In the following, we analyse the country-specific strategies toward a hydrogen economy by looking at the common design elements across all reviewed publications. Our analysis is structured by using four leading questions. First, we look at how hydrogen shall be produced (Section 3) and which applications will consume hydrogen (Section 3.2). Then we contrast how national strategies aim to meet demand with available supply (Section3.3). Lastly, we ask how policies can support the build-up of a hydrogen economy (Section 3.4).

3.1. How shall hydrogen be produced on a national level?

Commercial hydrogen production is not a novelty. The transformation of natural gas via steam methane reforming (SMR) is an important building block of modern refineries used for hydrocracking and hydrotreating to obtain different petroleum products. SMR, combined with the Haber-Bosch process, is also the standard production route for ammonia, with more than half of today's global fertiliser consumption being ammonia-based [20]. Due to the emission intensity of fossil-based hydrogen production, ammonia is one of the most-emission intensive chemicals, accounting for 49% of CO_2 emissions from global primary chemical production in 2020 [21]. Alternative production routes are needed for hydrogen to play an important role in the transition towards a climate-neutral economy. Two technology options for low emission hydrogen are available on an industrial scale to replace SMR (grey hydrogen) as the dominant production route and meet new demand: SMR combined with carbon capture technology (blue hydrogen) and the electrochemical process via electrolyser using renewable energy (green hydrogen). Pink and turquoise hydrogen are additional options under investigation and complement the colours spectrum of low-emission hydrogen. In the following, we provide a brief overview of these technology options referenced across different national hydrogen strategies.

Blue Hydrogen uses the conventional production route of grey hydrogen production, transforming fossil methane (CH_4) in the form of natural gas in a reaction with water (H_2O) as high-temperature steam (>1000°C) into hydrogen (H_2) and carbon dioxide (CO_2). This production pathway is often referred to as brown hydrogen if the process is based on the gasification of fossil coal. Instead of releasing the process emissions and energy-related emissions from heating the steam into the air, a carbon capture installation separates CO_2 from the exhaust gases. The main benefit of blue hydrogen is that existing installations for industrial hydrogen use can be retrofitted while continuing to process fossil natural gas. However, not all emissions can be captured. While the IEA assumes future capture efficiencies of up to 95% and higher [22], a recent study shows that currently used carbon capture approaches only marginally reduce the total greenhouse gas emissions caused by hydrogen production, and blue hydrogen can be more emission-intensive per unit of energy than natural gas [23]. Process and energy use optimisations of current capture designs would make blue hydrogen less emission intense than grey hydrogen but not a zero carbon emission technology. In terms of economics, the production of blue hydrogen will always require additional equipment and faces a higher energy consumption than grey hydrogen production. If captured CO_2 cannot be utilised on-site or by nearby consumers, it must be permanently stored underground in a suitable geological formation.

Green Hydrogen refers to hydrogen production via the electrolysis of water (H_2O) to separate hydrogen (H_2) and oxygen (O_2) using electrical energy from renewable sources. Two electrolyser types are commercially available, alkaline (AEL) or with polymer electrolyte membrane

(PEM/PEMEL). Solid oxide electrolysis (SOEL/SOEC) is a prospective additional technology currently under investigation. Among others, differences exist regarding operational flexibility and efficiency, stack lifetime, and current and future investment costs [24]. Even though news made the headlines in late 2021 that green hydrogen is temporarily competitive with grey hydrogen production in Europe due to high natural gas prices [25], [26], green hydrogen production on a commercial scale remains neglectable until now [22]. According to IRENA, decreasing investment costs, better access to low-cost renewable electricity generation, and higher electrolyser efficiencies are the main drivers for developing a green hydrogen economy over the next decades [27].

Pink Hydrogen combines electricity and off-heat generated by nuclear power plants to operate high-temperature electrolysers with improved process efficiency. Though small-scale on-site hydrogen production for self-use is common for nuclear power plants (see [28]), large-scale implementation is only at the feasibility study stage [29].

Turquoise Hydrogen is produced by the pyrolysis of carbon-based energy carriers, thermally decomposing them into their elementary components. Solid elementary carbon is a residual product, which is either of fossil origin if using natural gas or biogenic in the case of biomass. Catalysts could reduce the required process temperatures to 400-700°C [30]. However, the process is studied at a laboratory scale, and a small pilot is only planned for 2023 [31].

All national strategies specify which hydrogen production technologies are expected to be of importance. Green hydrogen is the dominant technology mentioned by all national publications. However, in some countries, its role is seen as secondary to blue hydrogen during the early phases of the transition towards the hydrogen economy. Australia, Canada, Colombia, and South Africa state the importance of fossil-based hydrogen production combined with carbon capture, benefiting from the local availability of natural gas and coal deposits. Also, countries without significant fossil resources, such as South Korea and Japan, present blue hydrogen as an important element of their national strategies. Both countries have in common that local conditions might not allow for large-scale national green hydrogen production using renewable wind and solar resources. Japan, for example, is one of the regions with the highest expected costs for green hydrogen production according to the levelized cost of hydrogen (LCOH) map published by the International Energy Agency (IEA) [32]. In contrast, many countries with a high renewable energy production potential only focus on green hydrogen, such as Chile, Morocco, and Spain. Very few countries mention and foster biomass as a potential feedstock for hydrogen or include nuclear energy as an option for pink hydrogen production. Here, the UK and Canada have a common long-term vision of nuclear in their energy mix. Additionally, Canada emphasises the high availability of low-cost biomass as motivation for including it as feedstock for hydrogen production.

Production technologies are often jointly stated with hydrogen production targets. Here, it's important to differentiate between long-term targets that define the role of hydrogen in a decarbonised energy matrix and intermediate targets for scaling up hydrogen production over the next decade. Europe's large economies, such as Germany (5 GW), the UK (5 GW), France (6.5 GW) and Spain (4 GW), have similar absolute intermediate capacity targets for 2030. While many other strategies don't quantify intermediate targets, the Chilean (25GW) and South African (11.7 GW) capacity targets for 2030 stand out compared to other national strategies. Germany (10GW) and South Africa (15 GW) also quantify domestic capacity targets for 2040. Across all strategies, long-term targets are stated as demand forecasts. However, only four of the reviewed 12 publications quantify targets beyond 2040, highlighting the increasing uncertainty of how and when the hydrogen economy will evolve.

Table 2: Hydrogen production pathways in reviewed national strategies

Country	**Hydrogen production method**	***Horizon***	**Capacity volumes**
Australia	SMR and brown coal with CCS and green hydrogen.	***2030***	N/S
		2050	
Canada	Coal and SMR with CCS and green hydrogen. Biomass gasification and nuclear as also mentioned.	***2030***	S/N
Chile	Production of green hydrogen	***2050***	S/N
Colombia	Green hydrogen and SMR with CCS.	***2030***	4 GW
		2050	N/S
France	Low-emission hydrogen (SMR with CCS) and green hydrogen.	***2028***	6,5 GW
Germany	Green hydrogen	***2030***	5 GW
		2040	*10 GW*
Japan	Brown coal and untapped fossil fuel resources with CCS, and green hydrogen	***2030***	N/S
		2050	
Morocco	Green Hydrogen	***2030***	N/S
		2050	
South Africa	Green hydrogen and SMR with CCS.	***2030***	11.7 GW
		2040	15 GW
South Korea	Production from LNG without specifying CCS. Production and (long-term) import of green hydrogen.	***2040***	N/S
Spain	Green hydrogen	***2030***	4 GW
			N/S
United Kingdom	Green hydrogen and CCUs	***2030***	5 GW
	Green hydrogen, CCUs, and increasing range of production (nuclear, biomass)	***2050***	N/S

3.2. Which applications and sectors are set to consume it?

Hydrogen is an energy vector with its very own unique characteristics. It is best used in applications tailored towards maximising hydrogen's energetic and non-energetic value. In the following, we differentiate between three distinct types of hydrogen use cases mentioned by national strategy and pathway publications. After a closer look at current uses of hydrogen, we present new hydrogen-based processes and potential applications for hydrogen as a thermal energy source across all sectors of the economy. The following categories are not exclusive, and use-cases overlap for some applications. However, they provide some guidance on how demand-side applications stated across the different national strategies can be categorised.

Hydrogen used as feedstock could be considered the low-hanging fruits for low-emission hydrogen consumption. No additional infrastructure and equipment changes are needed to replace emission-intensive grey hydrogen. In 2020, refining (44%), ammonia (37%), and methanol production (14%) accounted for almost the entire global demand, while most of the remaining hydrogen was consumed in the direct reduced iron (DRI) process for steelmaking (> 5%). The transport sector was only responsible for 0.02% of total demand [22].

Ammonia used to make fertiliser requires elementary hydrogen, mostly obtained by steam SMR of natural gas. Replacing this grey hydrogen with low-emission alternatives can significantly reduce the emission intensity of fertiliser production. In the case of today's refining processes, replacing grey hydrogen with low-emission alternatives cannot make the industry emission-neutral. Refining fossil fuels and using them for energetic purposes by combustion will always cause fossil emissions. Consequently, hydrogen use by today's refining processes is incompatible with an emission-neutral economy and only helps to reduce the carbon footprint of currently used refining processes.

The large-scale hydrogen consumption in the steel industry relies on a switch from blast furnaces to direct reduced iron (DRI) furnaces for primary steel production. In 2019, about 8% of global iron production stemmed from furnaces that used natural gas (CH_4) to refine ore rich in iron oxides (Fe_xO_y) to DRI. Natural gas reforming is used to produce syngas ($CO+H_2$) which acts as a reduction agent. Only changes to auxiliary processes are needed to replace syngas with hydrogen as a reduction agent that doesn't cause carbon monoxide. Thus, only water would be emitted as a by-product, and no CO_2 would be emitted.

Hydrogen used in fuel cells. Hydrogen fuel cells technologies are already commercially available and its use is tailored to hydrogen fuel cells for road transport, rail and potentially air and maritime transport. Here, hydrogen serves as a highly efficient energy carrier. Within the fuel cell, the reaction energy of oxygen (O_2) with hydrogen (H_2) released when forming water (H_2O) fuels an electric engine. In the case of two comparable passenger cars, the well-to-wheel energy efficiency of fuel a cell combined with an electric drive train (FCEV) can be up to 90% superior to gasoline combustion if green hydrogen is used [33]. In the case of rail transport, hydrogen can also play a key role in the decarbonisation of non-electrified railway lines where diesel trains are running and electrification is not technically or economically feasible.

Hydrogen for thermal use might be relevant for decarbonising applications requiring very high temperatures without another suitable low-emission alternative in sight. Theoretically, hydrogen combustion could fully replace fossil fuels and natural gas for energetic purposes, such as for residential heating, industrial furnaces or electricity production. However, low and medium temperature applications can be electrified efficiently with standardised equipment [34]. As shown in Figure 1, only the energy-intensive basic material sector, including the production of non-metallic minerals like cement, ceramics and glass, metals, and petrochemicals, relies predominantly on process temperatures exceeding 200°C. About 90% of the heat demand from all other industries is below this threshold. Also, hydrogen use for residential heating would always face the competition of direct electrification options, for example, highly efficient electric heat pumps. Scenarios for residential decarbonisation lead to very different outcomes in studies assessing long term electrification and hydrogen use potentials [35], [36].

Synthetic hydrocarbon production or other hydrogen-based chemicals, such as ammonia, can also form the basis of non-fossil fuel production for energetic purposes. Synthetic hydrocarbons have the advantage that today's combustion engine can be used with potentially emission-neutral fuels.

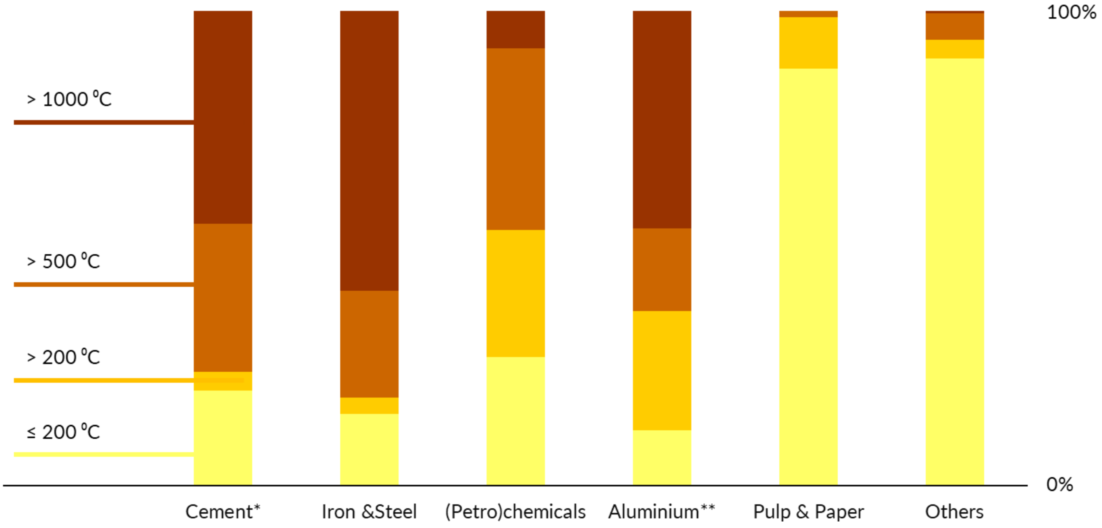

Figure 1: Process Heat consumption in EU industries per temperature band [37]. For cement, data for the entire non-metallic mineral sector is used. For aluminium, data for the entire non-metallic industry is used.

However, to bring life-cycle emissions to zero, the production process cannot rely on elementary carbon stemming from captured fossil emissions. Burning syntenic fuels containing fossil carbon means that fossil carbon enters the atmosphere in the form of CO_2 or other greenhouse gases. Instead, elementary carbon should be directly sourced from the atmosphere (DAC) or be from biogenic origins. Ammonia is an alternative combustion fuel that is not carbon-based, containing only atmospheric nitrogen and hydrogen molecules. Ammonia fuels need new engines, currently under development, to efficiently burn them[3]. A challenge related to all combustion processes is the formation of other greenhouse gases if engines are not operated under optimal conditions. NOx-emission, resulting from ammonia combustion, are 300 times more damaging to the atmosphere than CO_2 [40]. Especially for aviation and shipping, synthetic fuels are key elements of the decarbonisation strategies of the sector on an international scale.[4]

The production of synthetic hydrocarbons, such as consumable chemicals and polymers, is currently under development. By combining hydrogen with non-fossil carbon, either from direct air capture (DAC) or biogenic origin, emission-neutral hydrocarbons (C_xH_y) could be obtained [43]. Production processes are being tested in various pilot projects that use captured fossil carbon from conventional processes or waste streams as carbon sources [44].

National strategies state potential hydrogen applications with varying levels of detail for the 2030 horizon and beyond. Table 3 compares the different strategies based on the information about low-emission hydrogen use in current use-cases for new hydrogen-based technologies and thermal use and Table 4 and Figure 2 provides a picture of the quantitative targets of the revised national hydrogen strategies.

Among current uses cases for industrial-scale hydrogen applications, ammonia production is one of the most mentioned across all strategies. All but the South Korean strategy mention the importance of low-emission hydrogen for ammonia production. However, some countries, such as Japan, primarily consider ammonia as a transport fuel or liquid hydrogen carrier. The national strategy only mentions ammonia for industrial use cases for the long-term horizon. Replacing grey with low-emission hydrogen in today's processes is specifically mentioned by some

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[3] See, among others, ongoing work on ammonia engines by Mitsubishi [38] and Wärtsilä [39]

[4] See, greenhouse gas reduction strategies by IATA [41] and IMO [42].

strategies, for example, the Colombian, French, German, UK and Spanish publications. Here, the German strategy specifically states that the long-term target must be the use of hydrogen as a sustainable base material for the industrial sector until 2050.

Some publications introduce methanol as another chemical currently produced using hydrogen-rich syngas to be replaced by low-emission hydrogen. Today's industrial methanol production accounts for about 14% of global hydrogen consumption [22]. In contrast, its role in national hydrogen strategies is mainly linked to its role as a potential hydrogen carrier, liquid transport medium and fuel. Strategies quantifying mid-term national industry targets state replacement rates for current grey hydrogen use with clean alternatives. Both Colombia and France aim for a 40% share by 2030, whereas Spain contemplates a 25% share.

Primary steel production entirely based on hydrogen as an energy carrier and reduction agent is mentioned by most strategies as emerging technology and a potential source for hydrogen consumption in the intermediate and long-term horizon. It's therefore particularly interesting to understand which strategies don't mention steel production within the national context, namely Chile, Japan and South Korea. While the Chilean strategy identifies steel production as a potential use case for hydrogen, it doesn't consider technology implementation within the 2050 horizon. Industrial applications focus on the refining sector and ammonia production. In the case of South Korea, the national hydrogen strategy primarily focuses on the role of the Korean industry as a global technology provider for FCEV, fuel cells, and electrolyser technology. Only the current and future use of hydrogen in the petrochemical industry is explicitly mentioned. Japan mentions industrial use cases for the 2050 horizon but does not specify industrial sectors in greater detail.

An alternative low-emission option for powering the transport sector is synthetic fuels, which also justify long-term hydrogen consumption in the refining sector. Except for Morocco, its use is not considered for road transport, while all but the South Korean and Japanese national strategies highlight its role in maritime and aviation transport.[5] The role of synthetic fuels in aviation and ammonia as an energy carrier in the maritime transport industry is driven by the long-term decarbonisation strategies of the international air transport (IATA) and maritime associations (IMO) towards 2050 [41], [42]. First of all, air and maritime transport are global industries, so the direct or indirect alignment of national strategies with the international roadmaps does not surprise. Synthetic fuel production and its consumption in the form of ammonia or synthetic hydrocarbons are only foreseen for the long-term horizon in the Chilean, Colombian and Spanish strategies. Other countries indicate a need to invest and ramp up the technology in the 2030 horizon but only mention its large-scale use until 2050 (Australia, Germany, Morocco). Shipping and, to a lesser extent, aviation are only mentioned in the 2030 horizon if strategies highlight pilot or demonstration phase projects. The UK and Canada expect first trials for shipping before 2030, whereas France and South Africa emphasise R&D needs for the aviation and maritime industry.

Hydrogen for thermal energy use beyond synthetic fuels is mentioned by almost all national strategies in various forms, including power-sector applications, and direct combustion for heating in the industrial and residential sectors. Across all revised publications, hydrogen use for stationary thermal consumption only plays a small role in the 2030 horizon. The UK and France

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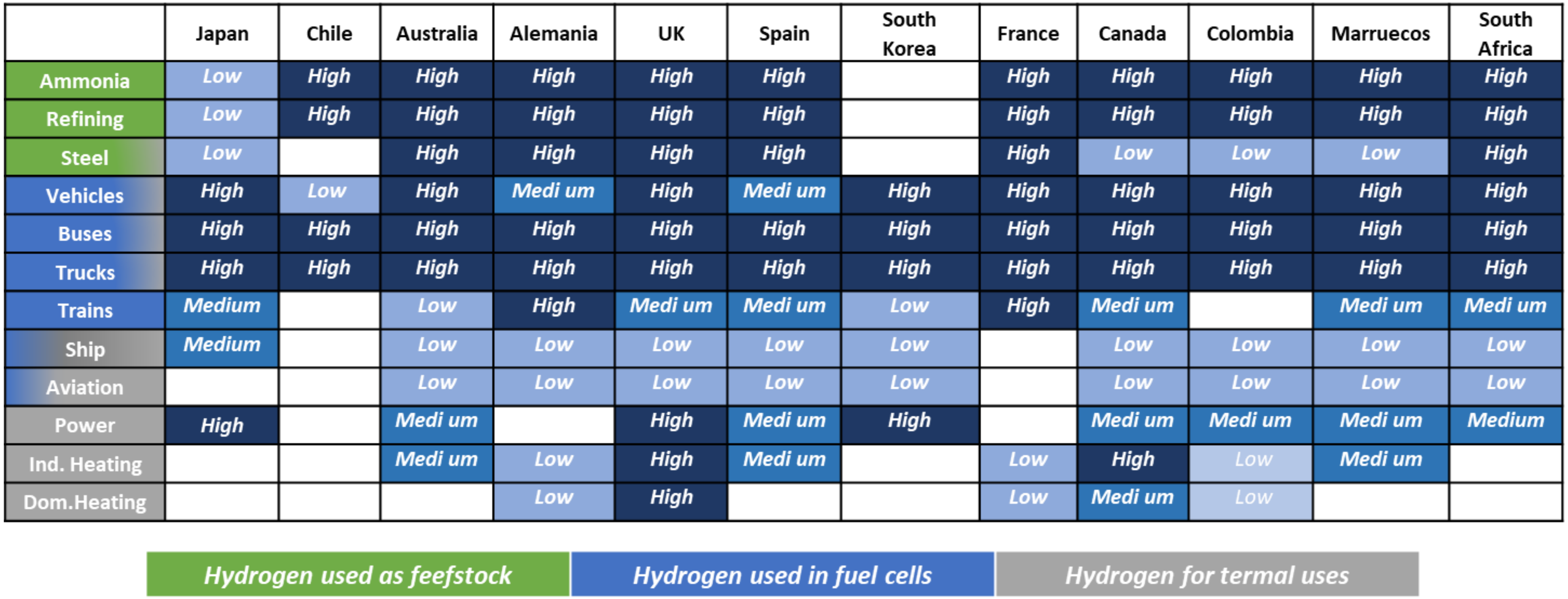
[5] The Japanese and South Korean strategies discuss fuel cell as an option for maritime transport.

are the only countries with specific consumption targets for the mid-term. A more prominent use case for hydrogen is power generation. Plans to explore this use case until 2030 are highlighted in many reviewed publications. Only in the French and Chilean strategies, the power sector is not seen as a potential off-taker. The South Korean and UK strategies detail two very different use cases for hydrogen use for electricity generation. The Korean publication only mentions stationary fuel cells at the residential and distribution system level as potential power generation technology. In contrast, the British publication states hydrogen combustion in cogeneration facilities as a hydrogen use case for the electricity sector. Many other strategies lean towards high-efficient hydrogen combustion as an alternative to natural gas power plants or remain technology-neutral. Most countries only foresee a greater role for thermal energy uses, such as in industrial applications, in the 2050 horizon only. The Australian, Canadian, German, Moroccan, and Spanish strategies mention hydrogen as a potential thermal energy source across all reviewed stationary applications.

Table 3: Overview of hydrogen priority use cases across different national hydrogen strategies



	Japan	Chile	Australia	Alemania	UK	Spain	South Korea	France	Canada	Colombia	Marruecos	South Africa
Ammonia	*Low*	*High*	*High*	*High*	*High*	*High*		*High*	*High*	*High*	*High*	*High*
Refining	*Low*	*High*	*High*	*High*	*High*	*High*		*High*	*High*	*High*	*High*	*High*
Steel	*Low*		*High*	*High*	*High*	*High*		*High*	*Low*	*Low*	*Low*	*High*
Vehicles	*High*	*Low*	*High*	*Medi um*	*High*	*Medi um*	*High*	*High*	*High*	*High*	*High*	*High*
Buses	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*
Trucks	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*	*High*
Trains	*Medium*		*Low*	*High*	*Medi um*	*Medi um*	*Low*	*High*	*Medi um*		*Medi um*	*Medi um*
Ship	*Medium*		*Low*	*Low*	*Low*	*Low*	*Low*		*Low*	*Low*	*Low*	*Low*
Aviation			*Low*	*Low*	*Low*	*Low*	*Low*		*Low*	*Low*	*Low*	*Low*
Power	*High*		*Medi um*		*High*	*Medi um*	*High*		*Medi um*	*Medi um*	*Medi um*	*Medium*
Ind. Heating			*Medi um*	*Low*	*High*	*Medi um*		*Low*	*High*	*Low*	*Medi um*	
Dom.Heating				*Low*	*High*			*Low*	*Medi um*	*Low*		

Hydrogen used as feefstock ***Hydrogen used in fuel cells*** ***Hydrogen for termal uses***

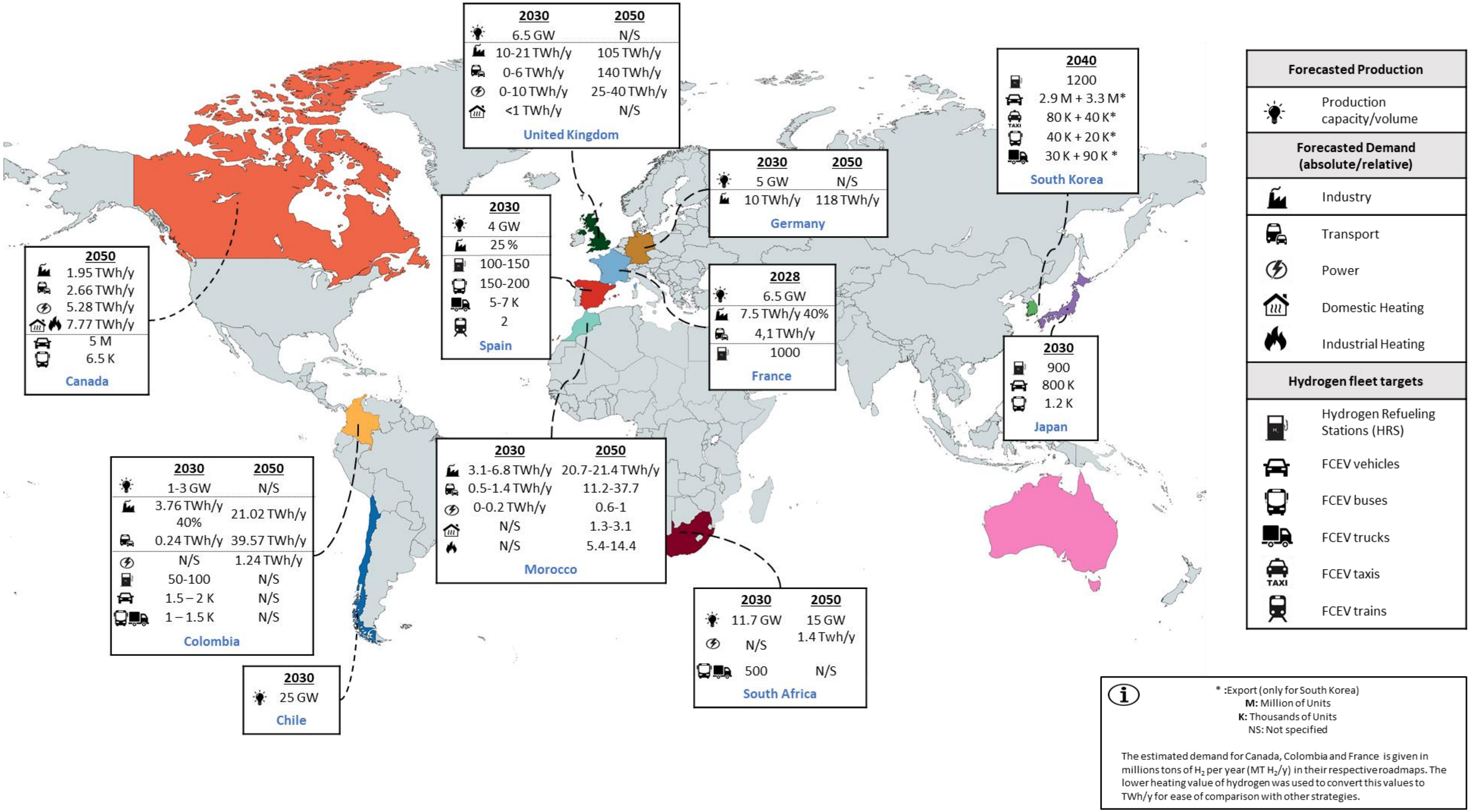
Low	*Not an important sector for the roadmap or its use is foreseen beyond 2040*
Medium	*Some specific applications are envisaged for 2030*
High	*Sector seen as a priority for the 2030 strategy*

Table 4. Overview of hydrogen use cases across different national hydrogen strategies

	Japan		Chile	Australia		Alemania		United Kingdom		Spain		South Korea	France	Canada		Colombia		Marruecos		South Africa	
	2030	2050	2030	2030	2050	2030	2050	2030	2050	2030	2050	2040	2028	2030	2050	2030	2050	2030	2050	2030	2050
Ammonia	🔴	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟡	🟢	🟡	🔴	🟡	🟡	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Refining	🔴	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟡	🟢	🟡	🔴	🟡	🟡	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Steel	🔴	🟡	🔴	🟡	🟡	🟡	🟢	🟡	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🔴	🔴	🟡	🟡
Vehicles	🟢	🟡	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟡	🟢	🟢	🟡	🟡	🟡	🟡	🟡
Buses	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟢	🟢	🟡	🟡	🟡	🟢	🟡
Trucks	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟢	🟢	🟡	🟡	🟡	🟢	🟡
Trains	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟡	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟡
Ship	🟡	🟡	🔴	🔴	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🟡	🟡
Aviation	🔴	🔴	🔴	🔴	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🟡	🟡	🟡
Power	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟢	🟢	🟡	🟡	🟢	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🟡	🟢
Ind. Heating	🔴	🔴	🔴	🟡	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🟡	🔴	🔴
Dom.Heating	🔴	🔴	🔴	🔴	🟡	🔴	🟡	🟢	🟡	🔴	🟡	🔴	🟡	🟡	🟡	🔴	🟡	🔴	🔴	🔴	🔴

Hydrogen used as feefstock	***Hydrogen used in fuel cells***	***Hydrogen for termal uses***

🔴 Not seen 🟡 Mentioned 🟢 Mentioned with absolute/relative values



* :Export (only for South Korea)
M: Million of Units
K: Thousands of Units
NS: Not specified

The estimated demand for Canada, Colombia and France is given in millions tons of H_2 per year (MT H_2/y) in their respective roadmaps. The lower heating value of hydrogen was used to convert this values to TWh/y for ease of comparison with other strategies.

Figure 2: Map of quantitative targets across reviewed national hydrogen strategies

3.3. How would demand be met with supply?

Hydrogen production requires hydrogen consumers and vice versa. However, meeting hydrogen demand by sufficient supply is not possible without looking at the transport infrastructure needed to connect both. In the following, we look at three different phases for matching demand and supply. Firstly, integrated production and consumption centres are, above all, relevant during the ramp-up of hydrogen production and need to be followed by the build-up of a regional and national hydrogen transport system. Lastly, the option to meet growing national demand with imports from abroad or sell national overproduction to consumers worldwide is seen as economically viable in the long run only.

Integrated production and consumption are the current status quo for most of today's hydrogen demand in industrial applications. Compared to grey hydrogen consumption, low-emission hydrogen production faces various locational constraints. Green hydrogen requires access to renewable energy sources, such as solar photovoltaic or wind farms. It also requires land availability to develop these facilities and a robust electricity infrastructure to transport the electricity to the electrolysers. Blue hydrogen relies on facilities to process captured emissions or store them permanently. Very few of today's industrial facilities fulfil integrated production and consumption requirements, such as the planned fertiliser plant with on-site green hydrogen production by Spanish companies Fertiberia and Iberdrola in Puertollano [45]. In the transport sector, expected to be the main consumer of hydrogen in the future [32], consumption is by design fully independent from production centres.

Hydrogen transport systems bridge the gap between production and demand. Historically, energy networks have first developed very locally. In a second phase, and only if required, networks are being extended towards an interregional or national level and beyond.[6] Due to its gaseous state, pipelines are the most efficient way to distribute hydrogen over short distances. However, pipelines require a certain transport volume to be economically viable. Pipelines also play an important role in connecting demand centres for fossil fuel and natural gas on a national level. Such existing natural gas infrastructure can be retrofitted to transport hydrogen instead [49], [50]. One option is to blend hydrogen with natural gas to transport and potentially consume both jointly, though many technical and regulatory questions about its practical feasibility remain [51]. Compressed or liquified hydrogen transport in trucks, trains or inland vessels is an alternative for distributing hydrogen over several hundred kilometres to consumption centres, such as hydrogen refuelling stations for vehicles [52], [53].

Hydrogen storage is an important element of transport systems, but storage applications differ depending on the storage need. Short term storage options include pressure vessels and within the pipeline system. Underground storage in salt or lined rock caverns or the (re)transformation of hydrogen to liquid or material-based hydrogen carrier can help to balance seasonal demand and supply fluctuations [54], [55]. National realities and circumstances, such as differences in hydrogen demand and supply profiles and the availability of existing and potentially retrofittable transport infrastructure, will be decisive for the composition of transport systems in each country.

Imports and exports of hydrogen in big volumes over distances beyond 1000 km and across bordering countries might be feasible with new or existing pipelines systems. However, for

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[6] See, for example, the historic development of electricity and natural gas infrastructure in Spain [46], [47]. Note, heat networks are an example for energy systems that are only operated on local level [48].

hydrogen to become an internationally traded commodity, it must be transported by ship. The blueprint for global hydrogen markets is liquified natural gas (LNG) trade, accounting for about 20% of European natural gas uptake in 2020 [56]. Export facilities in producing countries liquefy natural gas by cooling or pressurising it,[7] while import facilities reverse the process to feed the gas into the domestic pipeline systems. Obtaining liquid hydrogen is significantly more difficult since its boiling point is at −252.9°C, compared to -165 °C for natural gas. The transformation of hydrogen in liquid organic hydrogen carrier (LOHC) as transport liquid and its retransformation back into hydrogen at the destination are seen as a viable alternative to liquified hydrogen transport. Another alternative is the transport of Ammonia (NH_3) [32], [52]. All these options have in common that there is little to no experience concerning their suitability for economically viable maritime transport.[8]

National strategies do not place a strong focus on detailing integrated production and consumption centres but often imply the local character of hydrogen supply during the early phases of the transition. The UK strategy specifies that co-located applications without additional pipeline networks for connecting supply and demand will be the dominant use case before 2025, and one of the axes of the French strategy is the local supply of industrial hydrogen demand. Colombia emphasises the decentralised character of pilot plants. Other national publications highlight the local character of pilots for industrial demand, such as the Canadian strategy. The German strategy introduces the term "sandboxes" for pilots with novel technologies that operate in an isolated local regulatory environment to bring hydrogen applications to market readiness.

A summary of the storage and transport methods mentioned in the different strategies can be found in Table 5. For scaling up the hydrogen economy, road transport of hydrogen by truck might be key for linking demand and supply centres in the national context. However, across all reviewed publications, only Canada and South Korea and the UK detail the role of hydrogen tank trucks over the entire time horizon of their national strategies. All publications mention the importance of existing gas networks for the transition. Retrofitting existing natural gas networks and building new dedicated hydrogen pipelines is a transport solution to connect demand and supply centres on a regional and national level that is only framed as a medium and long-term solution.

Blending hydrogen with natural gas is introduced as a more short-term option for system-wide use. Nevertheless, blending has a very different role across all reviewed publications. France, in their National Energy and Climate Plan (NECP), and the UK quantify blending targets for the 2028 horizon, detailing concrete actions and pilots exploring blending options. Australia and Canada actively pursue first pilots and field trials for blending, whereas Chile only states blending as an option from 2025 onwards. Spain only mentions it as one potential solution. South Africa presents blending mandates for clean fuels or ammonia as an option to accelerate the transition. Canada also includes blending in their 2050 vision with a potential 86% share by volume in networks, which would imply that energy use is not expected to be fully emission-neutral until then. In sharp contrast, Germany and Morocco do not mention blending in their national strategies.

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[7] Based on the tanker design, LNG is either stored below its boiling point at ambient atmospheric pressure or at higher pressure and higher temperatures [57].

[8] A first liquified hydrogen transport vessel for test purposes has been built in Japan and loaded its first cargo for long-distance transport in Australia in January 2022 [58].

Table 5: Hydrogen and CO2 transport and storage solutions in national strategies

	Japan	**Chile**	**Australia**	**Germany**	**UK**	**Spain**	**South Korea**	**France**	**Canada**	**Morocco**	**South Africa**
Transport											
Dedicated Pipeline	**X**		**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**
Blending	**X**	**X**	**X**		**X**	**X**		**X**	**X**		**X**
Road transport					**X**		**X**		**X**		
Ships	**X**	**X**	**X**	**X**	**X**		**X**		**X**	**X**	
Storage											
High pressure vessels				**X**	**X**				**X**		
Liquified Hydrogen	**X**						**X**				
Hydrogen Carriers	**X**			**X**	**X**						
Underground geological storage			**X**		**X**				**X**	**X**	
CO_2 Transport and Storage											
CCUs infrastructure			**X**		**X**				**X**		**X**

*For the purpose of this table, only specific mentions on hydrogen transport and storage were considered. There are some documents such as the Spanish roadmap that review literature on hydrogen transport and storage without specifying the role of hydrogen in the strategy itself.

Some national strategies detail hydrogen storage options. Canada, Germany and the UK provide details for most potential storage options. At the same time, all other strategies don't consider storage at all or mention it to a very limited degree. The characteristics of storage will depend on the applications of hydrogen. For industrial applications, short-term storage will be used in pressurised tanks or as liquid hydrogen. On the other hand, if hydrogen is to be used as an energy carrier for seasonal energy storage, it will be stored in underground reservoirs as well as in hydrogen carriers.

One peculiar feature is that the Australian strategy, which places significant importance on blue hydrogen production using natural gas or coal as feedstock, are pipelines systems to transport captured CO_2 to potential long-term underground storage locations. The need for CO_2 pipelines is also included in publications of other countries that opt for blue hydrogen, such as Canada, Colombia, Japan, and the UK.

All reviewed national strategies have in common that their long-term vision contemplates global hydrogen markets with import and export flows across national borders. The future role each country foresees for itself depends on the expected production potential on a national level, its expected production cost compared to competitors and target markets, and considerations about the logistics of global hydrogen trade. Germany, South Korea, and Japan have in common that their strategies are directed towards ramping up local hydrogen production in the mid-term while acknowledging that national production will not be able to meet growing demand in the long run. The German publication is among the most determined about its import dependence stating that Germany will continue to import much of its energy from abroad as a basic premise for the national strategy. These three nations are knowledge economies with a similar vision of hydrogen technology providers and exporters. The second group of countries expects that local demand can be met by local supply in the medium and long run. The UK strategy mentions import and export potentials for the 2050 horizon, therefore remaining open about the country's role in global hydrogen trade flows. Spain and Colombia foresee that local production will predominantly be used to meet local demand until 2030, but potential overproduction can be exported in the long run. The third group of countries aims for a fully exported oriented hydrogen economy. Besides Australia, which has already started exporting liquified hydrogen to Japan in a pilot project [58], countries like Canada, Chile, and Morocco want to build an export-oriented hydrogen economy.

Whether based in Africa, the Americas or Oceania, exporting countries have identified two key markets for hydrogen imports: Europe and East Asia. Shipping as liquified hydrogen or in the form of ammonia or other hydrogen carriers has been identified as the predominant transport option by both importers and exporters to supply Japan, South Korea and potentially China with hydrogen. Both pipelines systems and shipping are seen as viable options for meeting future European hydrogen demand. Competition between both transport methods exists today for natural gas imports to Europe. However, the dynamics between regional pipeline supply to Central-European consumption centres from Morocco or Spain compared to hydrogen shipments from Australia, Chile, Canada or Colombia are highly uncertain. As one of the main import markets, Germany highlights the role of pipelines to meet demand with European supply or from partner countries bordering the Union and emphasises the need to foster global cooperation and build global supply chains. Based on the reviewed publications, import and export routes across the Americas are less clear. Canada, Chile and Colombia all consider the US as a potential target market. In contrast, a private sector roadmap for the US[9] expects the country to be a hydrogen exporter instead of an importer. Chile also plans to export hydrogen to other countries in Latin America (LATAM). With Colombia, only one of the other major economies in the region was included in this review, which plans an export-oriented hydrogen economy for itself. As a first-mover publishing its hydrogen strategy in 2020, Chile's export potential to the LATAM region might have to be revisited based on other countries' hydrogen strategies.

A summary of the strategies regarding import/export targets for hydrogen and its derivates can be found in the Table 5.

Table 6. Import/Export (I/E) targets and products.

	I/E targets	I/E products	Pipeline	Ship
Japan	N/S	H_2, NH_3 and LOCH		
South Korea	N/S	H_2		
Germany	EU Member States and other non-EU countries.	H_2, LOCH		
Spain	Europe	H_2	X	
Canada	California, Eastern USA, Japan, South Korea, China and Europe.	H_2, NH_3 and LOCH	X	X
Colombia	Asia, Europe (in lesser extend) and eventually USA.	H_2 , NH_3, CH_3OH, LOCH		X
Morrocco	Europe	H_2, Synfuels	X	X
South Africa	Japan,South korea, Europe	H_2		X
Chile	Europe, China, Japan, South Korea, USA, Latam (>2030)	H_2, NH_3, Synfuels		X
Australia	Asia	H_2, NH_3		X
UK	N/S	N/S		
France	N/S	N/S		

Import	**Export**	**Non Specified (N/S)**

H_2 Hydrogen**; NH_3** Ammonia**; LOCH:** Liquid Hydrogen Carrier**; CH_3OH** Methanol.

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[9] The private-sector US roadmap was developed with the input from 20 companies and organisations under the umbrella of the Fuel Cell & Hydrogen Energy Association [59].

3.4. How can policymaking support the process?

Demand and production targets are a big promise of today's governments for tomorrow's hydrogen economy. Today, low-emission hydrogen is a niche product, and there is a long way to go for large scale production and consumption. Electrolysers and carbon-capture installations are already available at a commercial scale. However, to meet national targets, the market penetration with low-emission hydrogen production technologies must experience a sharp growth over the upcoming decades that might only be achieved if governments provide favourable framework conditions. Direct support for developing a hydrogen economy can take various forms that fall into one of the following main categories described across the reviewed national hydrogen strategies.

Public funding covers a wide range of measures that translate into financial benefits to the private sector or end-consumers for developing, producing, or using hydrogen technologies and applications. By providing ***R&D funding*** to universities, research institutes and the private sector, countries can help bring the technology to market readiness. As soon as commercially available, direct ***subsidies*** or ***tax incentives*** can help make commercially available hydrogen technologies competitive with conventional alternatives. Another approach towards using public funding is ***public procurement*** policies. The government can indirectly fund technology providers and create hydrogen demand by introducing public procurement criteria that favour hydrogen technologies.

A price for carbon emission, either in the form of a ***carbon tax*** or an ***emission trading system,*** helps make low-emission hydrogen technologies and their use cases competitive compared to conventional emission-intensive alternatives. Rather than direct support for hydrogen, carbon pricing increases the cost for conventional use cases of fossil energy, thereby improving the business case for all, not just hydrogen-based, low-emission options.

Rules and regulations for hydrogen applications can provide the legal basis for safe and environmentally friendly hydrogen use and timely hydrogen infrastructure development. A ***regulatory framework***, among others, for hydrogen purity, design requirements of hydrogen-based applications, permitting procedures, its taxonomy for reducing emissions and markets can be based on common ***standards*** that ultimately result in ***mandates*** for hydrogen use in certain applications. ***Guarantees of origin*** (GOs) to certify low-emission hydrogen production is one approach to demonstrate low-emission characteristics allowing markets to classify low-emission hydrogen products and governments to establish consumption mandates. Here, ***regulatory sandboxes*** offer the possibility to test and pilot the required regulatory changes.

Public-private partnership is an umbrella term for policies that encourage close cooperation between the governments and public institutions with the private sector. However, the identified need for a joint public-private approach must be followed and supported by concrete policy actions to enable a hydrogen economy.

A summary of the policies proposed by each government can be found in Table 7.

Table 7: Summary of policy options mentioned across reviewed national hydrogen strategies

	Japan	**Chile**	**Australia**	**Germany**	**United Kingdom**	**Spain**	**South Korea**	**France**	**Canada**	**Colombia**	**Morocco**	**South Africa**
1. R&D funding	X	X	X	X	X	X		X	X	X	X	X
2. Public-private partnerships	X	X	X	X	X	X		X	X	X	X	X
3. Framework for regulation and standardisation	X		X	X	X	X		X	X	X	X	X
4. Subsidies/funds for commercialisation			X	X	X	X		X	X	X	X	X
5. Carbon tax or emission trading system	X	X		X	X	X			X	X	X	X
6. Guarantees of origin (GOs)		X	X			X				X		X
7. General tax incentives			X	X						X	X	X
8. Public procurement policies						X	X	X			X	X
9. Mandates					X		X	X	X			X
10. Regulatory sandboxes			X	X								X

All national strategies included in this review recognise the need for governmental support. Nevertheless, the details about the policies mentioned above differ significantly across these publications. While countries not mentioning a specific policy, option does not mean that it does or will not be important for national policymaking, the following review highlights those policies that national governments consider particularly important for the transition.

Today, low-emission hydrogen is not an economically viable alternative for most energetic and non-energetic use cases. As such, making available additionally **R&D funding** is the most mentioned policy option across all national strategies. Only the South Korean publication does not specify these funding needs. While R&D funding seems to be of high importance for almost all of the reviewed countries, the willingness to provide public funding for the commercialisation of hydrogen technologies via regional or national funds is not explicitly stated by the Japanese and Chilean strategies. The Japanese strategy emphasises research and private-sector driven technology development. Due to the framing of the publication, the need for public funding is not explicitly mentioned but only hinted at. The situation is a bit different in the case of the Chilean strategy. The most ambitious with regard to mid-term targets for 2030 (25 GW, see Figure 2**Error! Reference source not found.**), but falling short on detailing how to attract the required private sector investments.

A successful ramp-up of a hydrogen economy relying on **public-private partnerships** is the second most discussed policy option. However, national strategies remain highly unspecific on how such partnerships may look in practice. Chile envisions public-private coordination as key for further detailing how the transition may take place. In contrast, Australia sees such partnerships in the context of infrastructure, assets and service provision, being the only publication clearly defining the objective of public partnerships in its strategy.[10] Spain mentions such partnerships for R&D funding, Canada for public transport and South Africa additionally for creating markets and future hydrogen exports. All strategies have in common that they lack further details on how such partnerships could be designed, implemented, and contribute to developing a hydrogen economy.

Providing a regulatory basis for hydrogen applications is a very broad topic. However, many national strategies state that **developing a regulatory framework** and standardising multiple aspects of a hydrogen economy are important but don't provide many details. Australia frames its approach as responsive regulation, identifying the regulatory needs for efficient supply chains, a supportive investment environment, training and safety standards. Germany identifies regulatory needs in various areas, including markets and infrastructure, codes and standards for applications and, in particular, the operation of carbon capture infrastructure. The UK takes one step further and specifies that a Hydrogen Regulator Forum is to be created that develops solutions for regulatory challenges. Among others, Spain highlights the need for a regulatory framework that addresses the interfaces between hydrogen, the electricity and the gas grid. Canada points out that the existing patchwork of national regulations affecting the hydrogen economy must be streamlined into a cohesive framework. In contrast, Colombia's strategy identifies infrastructure construction and refuelling stations as potential areas that must be addressed by new legislation.

The UK, France, Canada and South Africa have in common that their revision of the regulatory framework also covers blending, the potential mixture of hydrogen with natural gas within the existing gas grid. For all these countries, required policy actions go beyond standard-setting and imply mandates for blending. In case the UK mandates on the consumption level are specified further. They could lead to the obligation to, for example, change heating equipment at the residential level that can cope with a blended gas supply.

Public procurement is another way to provide public funding mentioned by less than half of the reviewed publications. Although all roadmaps highlight the importance of public procurement, most of them do not specify exactly of what type. The focus is primarily on the transport sector, including public transport fleets and government vehicle fleets, as in the case of Spain, France, South Africa and South Korea. South Africa and South Korea also mention the use of fuel cells in public buildings.

Guarantees of Origin (GOs) are also mentioned in six of the twelve strategies studied. Australia, Chile, Colombia and Morocco mention an international guarantee of origin system to promote their exports, giving an added value to green hydrogen. In the case of Spain, the national strategy refers to a potential European GOs scheme. Several hydrogen certification initiatives already exist in Europe, the most prominent of them being CertifHy, an EU voluntary scheme for the certification of hydrogen as RFNBO (Renewable Fuel of Non-Biological Origin) according to the European Renewable Energy Directive. Lastly, GOs are also mentioned in the South Africa roadmap, but it is not specified if they aim for an international, national or regional system.

General Tax Incentives aim to attract investment and develop competitive projects. For example, in the case of Colombia, both green and blue hydrogen will have some tax benefits, including exemptions from paying value-added tax (VAT). Germany proposes to exempt

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[10] A long-term contract between a private entity or consortium and a government, typically used by governments to pay for the delivery of public infrastructure, assets or services (SOURCE).

electricity used for the production of green hydrogen from taxes, levies and surcharges, specifically, the EEG tax (Erneuerbare-Energien-Gesetz), which is usually applied to all energy producers to finance renewable energy plans. Australia mentions the promotion of blending, highlighting revenue arrangements currently applied to hydrogen and committing to reviewing them in the future. South Africa has a taxation mechanism that can help deploy hydrogen-related technologies, including R&D incentives, automotive subsidies or the consideration of hydrogen clusters as special economic zones. Latter is also described in the Moroccan strategy. South Korea aims to use tax benefits to support domestic fuel cells with favourable electricity tariff/taxation schemes to ease the burden on the electrical grid.

Mandates are mentioned by less than half of the reviewed strategies, mainly being applied to the transport sector and for blending hydrogen in natural gas networks. UK mentions a mandate for hydrogen blending in aviation fuel and seeks to detail its proposal based on the Sustainable Aviation Fuel (SAF) blending mandate consultation [60]. In the same line, the UK strategy proposes to include hydrogen derivates in the Renewable Transport Fuel Obligation (RTFO). The RTFO encourage fuel suppliers to ensure that a percentage of the fuel comes from renewable and sustainable energy sources.

The UK and Canada mention zero-emission vehicles (ZEV) mandates, which means that a proportion of a carmaker's sales will have to come from electric or hydrogen vehicles. In the UK, the mandate is part of the net-zero strategy and will be introduced in 2024. It will introduce a credit system, which allows manufacturers who have problems meeting their targets to buy credits from other manufacturers. In Canada, the government announced a mandatory target for all newly sold light-duty cars and passenger trucks to be zero-emission by 2035. ZEV mandates have already been implemented in some provinces, namely Quebec and British Columbia.

Blending mandates in natural gas networks are mentioned by Canada, UK and South Africa strategies, the latter including ammonia in addition to hydrogen. In the power sector, South Korea proposes the installation of fuel cells at public institutions and new private buildings, while no country mentions mandates for the industrial sector. Some countries set relative targets for low-emission hydrogen consumption in the industrial sector (see Figure 2) but in no case are they mandates or have any legal implications.

Regulatory Sandboxes only have a prominent role in the German, Australian and South African strategies. Compared to the other two national strategies, Germany provides a much more detailed description of the use of regulatory sandboxes and their importance in enabling the hydrogen economy. A budget of 600 million euros will be devoted to regulatory sandbox projects between 2020 and 2023, specifically mentioning their role in bringing Power-to-X (P2X) technologies to market readiness.

4. Discussion

All reviewed national hydrogen strategies detail how country-level hydrogen economies can emerge over the next decades. Our review shows that key questions about how to enable hydrogen production and consumption are answered very differently based on the specific national context. However, some common trends can be observed across most reviewed publications which can provide valuable insights into the emergence of a hydrogen economy.

The preferred option for low-emission hydrogen production is closely linked to the availability of energy resources within the country. Countries with a high potential for low cost solar and wind energy production tend to favour green hydrogen, while for countries with preferential access to fossil fuel resources, blue hydrogen and other carbon-capture options are more relevant. This observation is not universal, and countries put very different emphasis given their available resources.

Except for Chile (25 GW), countries see the upcoming decade until 2030 as a period of technology piloting and the construction of first large scale hydrogen production facilities. In parallel, the expected demand until 2030 is relatively low and limited to very few specific applications in industry and transport. Targets and objectives beyond 2030 are stated in various national strategies but tend to describe a high-level, long-term vision of a hydrogen economy only. Though all strategies are motivated by national commitments to emission reductions and efforts to keep global warming below 1.5 °C, their ambitions are more focused on what is needed over the next decade to lay the groundwork for the emergence of a hydrogen economy after 2030.

The role of the national hydrogen economy in a future global hydrogen market is an important common element across most reviewed publications. Especially for potential hydrogen exporters, such as Australia, Chile or Colombia, the analysis of long-distance maritime transport options of hydrogen is highlighted prominently within their strategies. Boundary conditions and the economics for global hydrogen trade flows are still highly uncertain. Hence, for the 2030 horizon, the emphasis in national strategies should primarily be on how local hydrogen demand can be met with local production by connecting demand centres with the closest available sources for competitive low-emission hydrogen. Import needs are expected beyond 2030 but will only become relevant if national hydrogen economies have developed to such an extent that national resources for competitive low-emission hydrogen supply and distribution are not sufficient.

National hydrogen economies require public support policies. Our review shows that most of the discussed policy elements across all strategies support technology development and first commercial-scale deployment. The emphasis is on R&D funding and other innovation subsidy schemes. Policies needed to establish the rules of a hydrogen economy, such as the development of a regulatory framework or a certificate of origin system, are also part of many national agendas. However, a clear vision for the functioning of a national or international hydrogen economy parallel to existing energy systems is not presented in any reviewed strategy. This doesn't mean that such a long-term policy perspective is missing. The need for additional policies will evolve depending on how, when, and the extent to which a hydrogen economy can contribute to achieving national and global climate policy targets.

National hydrogen strategies are motivated by long-term climate policy targets. These long-term visions for a climate-friendly economy often dominate the narrative and put the latest innovations in the field of hydrogen production and consumption technologies in perspective.

However, this narrative shifts the focus away from what national strategies can and should provide; a clear roadmap for establishing the favourable technical, economic and regulatory framework conditions on a national level for scaling up the hydrogen economy beyond 2030.

Our review and analysis of different design elements in national hydrogen strategies can help policymakers that are tasked with exploring the role of hydrogen in their own national context. Furthermore, we want to highlight that these national strategies point out many unanswered questions about the emergence of a hydrogen economy that requires academia, policymakers and industry to join forces to identify the needs, barriers and potentials for low-emission hydrogen production, trade and consumption.

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