sustainability

MDPI

Article

How Green Are the National Hydrogen Strategies?

Wenting Cheng [1,*] and Sora Lee [2]

[1] College of Law, The Australian National University, Canberra, ACT 2601, Australia
[2] School of Regulation and Global Governance (RegNet), The Australian National University, Canberra, ACT 2601, Australia; Sora.Lee@anu.edu.au
* Correspondence: wenting.cheng@anu.edu.au

Abstract: Since Japan promulgated the world's first national hydrogen strategy in 2017, 28 national (or regional, in the case of the EU) hydrogen strategies have been issued by major world economies. As carbon emissions vary with different types of hydrogen, and only green hydrogen produced from renewable energy can be zero-emissions fuel, this paper interrogates the commitment of the national hydrogen strategies to achieve decarbonization objectives, focusing on the question "how green are the national hydrogen strategies?" We create a typology of regulatory stringency for green hydrogen in national hydrogen strategies, analyzing the text of these strategies and their supporting policies, and evaluating their regulatory stringency toward decarbonization. Our typology includes four parameters, fossilfuel penalties, hydrogen certifications, innovation enablement, and the temporal dimension of coal phasing out. Following the typology, we categorize the national hydrogen strategies into three groups: zero regulatory stringency, scale first and clean later, and green hydrogen now. We find that most national strategies are of the type "scale first and clean later", with one or more regulatory measures in place. This article identifies further challenges to enhancing regulatory stringency for green hydrogen at both national and international levels.

Keywords: national hydrogen strategies; green hydrogen; blue hydrogen; carbon capture and storage; clean hydrogen; guarantee of origin; certification; phasing out

Citation: Cheng, W.; Lee, S. How Green Are the National Hydrogen Strategies?. *Sustainability* **2022**, *14*, 1930. https://doi.org/10.3390/su14031930

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 27 December 2021
Accepted: 24 January 2022
Published: 8 February 2022

1. Introduction

Hydrogen has emerged as a promising yet controversial energy source. It can help tackle various critical challenges in climate transition. Hydrogen extends the scope of climate transition to sectors that electrification of energy cannot reach because hydrogen can be used to decarbonize hard-to-abate sectors, such as long-distance transport, and heavy industry, such as steelmaking. It can also be used to support the integration of renewables and provide long-duration energy storage to increase power system flexibility It can replace fossil fuels as a zero-carbon feedstock in chemical and fuel production [1]. It has been considered an enabler of the grand transition that fills a "missing link" in the decarbonization roadmap [2].

So far, most hydrogen production still stems from CO_2-intensive processes based on fossil fuels [3]. The role of hydrogen in a low-carbon future has been examined by quantitative studies [4–8]. However, the prospect that hydrogen would contribute to emission reduction should not be taken for granted. Scientific knowledge has shown that hydrogen does not automatically qualify as a game-changer to address the climate challenge. Hydrogen is considered the most promising energy source in the coming years, yet carbon emissions of different types of hydrogen vary dramatically depending on their production methods and different scopes for emission calculation [9,10]. Color-band terminologies are used to differentiate types of hydrogen on the basis of production methods enabled by current technology: gray hydrogen from coal gasification, blue hydrogen from steam methane reforming (SMR), and green hydrogen from electrolysis water using renewable energy [7] (Figure 1). In addition, hydrogen produced from nuclear power is referred to as purple hydrogen. Prominently, different production methods have different climate implications as they are associated with different levels of carbon footprint.

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 1. The hydrogen color spectrum and indications for carbon emissions [11].

Many of the national hydrogen strategies state the importance of the emerging hydrogen industry in contributing to their national decarbonization objectives. Given the different climate implications of the hydrogen production pathways, it is essential to understand how the national hydrogen strategies are implementing or are expected to implement the stated decarbonization objectives. This is the central question of this paper.

So far, the color-band hydrogen terminologies based on production methods are often discussed *as fact and evidence*, rather than as *a commitment implemented through stringent regulation*. While scientists believe that only renewable energy-based green hydrogen can be truly clean, blue hydrogen is still considered essential to an incremental transitional pathway, as it is associated with larger volumes and lower cost, as well as competitiveness, particularly for countries with an export market, such as Norway [12] (p. 3). Even emissions intensity varies dramatically with different capacities of carbon capture and storage (CCS, in other contexts also referred to as carbon capture usage and storage, CCUS) which leads to continuous debate about "how green is blue hydrogen?" [13]. As shown in our analysis, many countries envisage blue hydrogen as an important steppingstone in their overall hydrogen deployment, now and here, in the hope that renewable energy-based green hydrogen would eventually be phased in, in the future. However, the techno-economic analysis of fossil-fuel hydrogen produced with CCS has revealed a dilemma: if carbon-capture rates are low, there is a risk of lock-in by scaled high-emissions fossil-fuel hydrogen; if capture rates are high, there is a risk of stranded assets as hydrogen production with CCS may never become competitive [10].

As early as 2014, it was pointed out that growing evidence supports the view that, by 2050, the world will be able to rely just on energy efficiency and renewable sources to meet all its energy demands. "The big question is whether we have the collective political-economic will and courage to wean ourselves off fossil fuels and nuclear power, in the overarching interest of preserving our climate and achieving a sustainable way of living on this earth" [14] (p. 483). This question remains the major challenge. To examine the extent to which national hydrogen strategies have directly confronted this challenge, it is important to understand not only the targets and scale of the strategic deployment of hydrogen [15] but also how decarbonization as a normative aspiration is implemented through regulatory measures in the context of competing interests and power asymmetries.

In this article, we propose a typology of regulatory stringency for green hydrogen in national hydrogen strategies, which contributes to the literature by providing a framework to measure commitment and regulation of countries' national hydrogen strategies for decarbonization through and within the hydrogen industry. Despite the stated limitations of the current typology, it sets up a comprehensive framework with identified key regulatory measures that could contribute to a more stringent green hydrogen regulation, including those differentiating renewable hydrogen, enabling renewable hydrogen-related innovation, and discouraging fossil-fuel hydrogen. We also put green hydrogen regulatory stringency in the context of energy trilemma and discuss further challenges to enhancing green hydrogen regulatory stringency.

2. Materials and Methods

2.1. National Hydrogen Strategies and Decarbonization Objectives

As of October 2021, 28 jurisdictions in the world had promulgated national-level hydrogen strategies or visions [16,17], including Australia [18], Canada [19], Chile [20], Colombia [21], the Czech Republic [22], the European Union (EU, at the regional level) [23], Finland [24], France [25], Germany [26], Hungary [27], India [28,29], Italy [30], Japan [31], Morocco [32], the Netherlands [33], New Zealand [34], Norway [35], Paraguay [36], Poland [37], Portugal [38,39], the Republic of Korea [40], Russia [41,42], Slovakia [43], Spain [44], Ukraine [45], the United Arab Emirates (UAE) [46,47], the United Kingdom (UK) [48], and the United States (US) [49]. Many countries issued their national hydrogen strategies to fulfill multiple strategic objectives, including but not limited to decarbonization. The literature so far has discussed country-specific hydrogen strategies, for instance, analyzing Polish hydrogen strategy in the context of the EU's regional strategies [50]. Country-specific techno-economic analyses of the development of the hydrogen industry also refer to national hydrogen strategies as important agenda-setting documents in their analysis [15,51,52]. The geopolitics of hydrogen have been analyzed [53] and some analysis maintains that the geopolitics of hydrogen is analogous to new oil in the future [54]. However, making such an analogy may lead countries to compete only on price without considering the climate consequences of fossil-fuel-based hydrogen. Horizon scanning reports on national hydrogen strategies [11,16], given their breadth of coverage, only briefly mention the decarbonization objective, without in-depth analysis of how these objectives would be implemented. There has been analysis of the green transition in national hydrogen strategies in European member states [55], but the focus is very broad on general social economic impacts, including not only carbon emissions but also new job creation and value added in the domestic economy. There have also been discussions on the development of hydrogen at the regional level, in Africa [56] and Asia [57]. There is a significant gap in the existing literature on national hydrogen strategies about the implementation of the decarbonization objectives and their relative regulatory stringency.

Most hydrogen strategies have claimed that mitigation of climate change through the development of the hydrogen industry is among the desirable objectives they want to achieve. However, underneath the apparent universalism of "sustainability" or "carbon neutrality" goals is "an uneasy tension among economic, environmental, and social challenges that is far from synergistic" [58] (p. 1177). There is a real risk of symbolically claiming the objective of decarbonization while not attempting to eliminate fossil-fuel hydrogen. The science of the climate crisis has urged public and private regulations to grant a distinctive status to the problem [58]. The regulations, in this case, include regulatory measures designed or envisaged by the national hydrogen strategies to achieve the goal of decarbonization.

2.2. Green Hydrogen Regulation in National Hydrogen Strategies

On the basis of the text of national hydrogen strategies and relevant literature, we identify three major regulations (fossil-fuel penalties, certifications, and exclusive renewable hydrogen enablement) that are relevant to achieving the decarbonization objectives via hydrogen.

- Penalties for fossil fuel

According to an International Renewable Energy Agency (IRENA) report in 2018, over 95% of hydrogen was being produced from fossil fuels, primarily from SMR of natural gas (48%), but also from oil (30%) and coal gasification (18%) [59] (pp. 13–14). The proportion of low-carbon hydrogen rose to 10% in 2020, including hydrogen produced from coal and natural gas with CCUS. The proportion of low-carbon hydrogen is expected to be 70% in 2030 globally, with half produced from electrolysis and the remainder from fossil fuels with CCUS. However, this ratio varies substantially between regions [60] (pp. 75–76).

The literature indicates that high emission intensities are associated with clean [10] or blue hydrogen [13]. If countries are serious about decarbonization through hydrogen, they need to deviate from their existing pathways of depending on fossil fuels for hydrogen production of any kind, including investing in CCS technologies. This is the only way they can prevent similar failed government initiatives such as clean coal [61]. However, while universally acclaiming the contribution of hydrogen in decarbonization, countries are not clear about their position on fossil-fuel hydrogen. This can even be illustrated by the most recent United Nations Framework Convention on Climate Change (UNFCCC) COP 26 held in November 2021 at Glasgow. The Glasgow Breakthroughs set a series of sector-specific common targets [62], which cover five key economic sectors including power, road transport, steel, hydrogen, and agriculture. These sectors account for more than 50% of global greenhouse gas (GHG) emissions. Specific to hydrogen, the target is that affordable renewable and low-carbon hydrogen will be available globally by 2030. Countries that are committed to the Glasgow Breakthroughs include Australia, Belgium, Canada, Chile, China, Denmark, Egypt, the EU, Finland, France, Germany, Guinea Bissau, India, Ireland, Israel, Italy, Japan, Kenya, Lithuania, Norway, Mauritania, Morocco, Namibia, the Netherlands, New Zealand, Panama, the Republic of Korea, Slovakia, Spain, Sweden, the UK, and the US, among which 18 have issued their own hydrogen strategies. However, the Glasgow Breakthroughs are ambiguous about the relative proportions of renewable hydrogen and low-carbon hydrogen and the emissions intensity thresholds for low-carbon hydrogen. They do not mention the proportion of fossil-fuel hydrogen without CCS either.

Given that hydrogen that is produced from renewables can provide the best opportunity for a zero-emissions fuel and genuinely contribute to the decarbonization objective [63], we examine penalties for fossil fuels as a context for the flourishing of renewable hydrogen. This context is important because the expectation of penalties for fossil fuels will project expectations of diminishing profitability and ultimately change the course of the fossil-fuel industry. It will encourage genuine participation in the energy transformation, rather than subverting the clean hydrogen future with a fossil-fuel-based one [64]. While the ultimate penalty is a concrete agenda to phase out-fossil fuel hydrogen (including so-called blue hydrogen, the production of which is associated with CCS), no country has pledged to do so. We, therefore, identify two proxy indicators that can be representative of a national hydrogen strategy's intention to quit fossil-fuel hydrogen: coal phasing-out timelines and carbon pricing.

Coal phasing-out timelines are the timeframe in which countries plan to halt the construction of new plants and manage the decline in emissions from existing assets [65] (p. 57). From a regulatory perspective, coal phasing out is a command-and-control measure of qualification cancellation. It will guarantee the elimination of the most emission-intensive hydrogen production, through coal gasification, no matter whether CCS is involved. Carbon pricing refers to initiatives that put an explicit price on GHG emissions as a value per ton of carbon dioxide equivalent (tCO_2e). Carbon pricing [66] is usually in the form of cap and trade, such as the EU's emission trading system (ETS), or a carbon tax.

- Hydrogen certification

Hydrogen certification schemes are sometimes referred to as guarantees of origin (GOs). Certifications are used to differentiate renewable, low-carbon, and other types of hydrogen because, once the hydrogen is produced, one cannot distinguish the carbon emissions embedded in the hydrogen production process from the end products. Therefore, like organic foods and forestry products, certifications are essential to enhance traceability [67], in this case, embedded carbon emissions. In addition, certification will enable consumers to be sure of the nature of hydrogen they are purchasing (either as personal preference or legal obligation) and may facilitate a secondary market in certifications themselves [68]. The EU was the first to develop its hydrogen certification—CertifHy. Many other countries have followed this market-based voluntary mechanism to enhance transparency and traceability of embedded emissions in hydrogen production [9,69]. There are many unresolved issues concerning the design of a certification regime, as identified in the Australian Hydrogen Guarantee of Origin Discussion Paper [70], including the coverage of emission scopes, carbon accounting frameworks, and treatment of offsets. This study focuses on the primary function of certification as labeling to signal the broad differentiation between different types of hydrogen, based on emissions intensity. If there is no certification scheme in place or envisaged, it means that a national hydrogen strategy has no intention to differentiate hydrogen based on embedded carbon emissions. If there is such a scheme, we go into the details of the certification scheme—what is certified against (renewable hydrogen, low-carbon hydrogen, clean hydrogen, or blue hydrogen etc.), reference emissions thresholds, carbon accounting system boundaries, etc. As all hydrogen certifications available so far are voluntary, we do not further differentiate the enforceability of the certification schemes.

- Innovation enablement: technology neutrality and beyond

Hydrogen technology breakthroughs are essential for scaling up the hydrogen industry. Many jurisdictions have announced enablement measures to support technological innovation. Given the different production methods for hydrogen, different technologies are also associated with different prospects of carbon emissions (Figure 2). Some technologies are specifically associated with fossil-fuel hydrogen production, including CCS, new technologies to separate oxygen from the air, and, in the case of natural gas, the water, and CO_2 from combustion products [71]. Given that RD&D is costly, and infrastructure built based on such technologies will support the continued use of fossil fuel, it is a crucial decision to make now whether to invest time, personnel, and capital to enable innovation of such technologies at all. However, in many cases, countries allowing "low-carbon" or "clean" hydrogen tend to support fossil-fuel hydrogen-associated technologies in the short term, often based on the argument of technology neutrality [8,72].

The principle of technology neutrality appears in many of the national hydrogen strategies as the guiding principle to enable technological innovation, in hydrogen technologies, as well as related infrastructure. This principle is not new; it has been used to guide a free and competitive scenario among all technically feasible solutions [73]. Technology neutrality is defined from a perspective of legal functionalism: "laws should refer to the effects, functions or general characteristics of technology, but never to a particular type or class of technology" [74] (p. 1685). For new technologies that are not currently developed or even imagined, a technology-neutral approach would automatically extend the application of existing law and regulation to future technologies to maintain the longevity of the law "a technology-neutral approach to legal drafting involves a description of the result to be achieved without specifying the technology to be employed or regulated" [75] (p. 18). Therefore, when applying this principle in practice, a noninterventionist approach is advised to address market competition, where policy may not favor any particular means of achieving the desired goal. Instead, the regulation should equally support all methods capable of achieving this outcome [76]. While the functionalist and future-oriented approach does resonate with prospective hydrogen technology breakthroughs to produce hydrogen from various processes, the ways that national hydrogen strategies and lobbyists from the fossil-fuel industries interpret this principle [72] have always narrowly defined the objective, i.e., that a commodity could deliver its use-value, not a fuel that could achieve a certain level of emissions intensity. Therefore, the principle is reduced to mean that renewable hydrogen and fossil-fuel hydrogen should be equally treated, no matter how different their emissions intensities are, now that there is no international convergence around a single preferred technological approach [10]. This principle has been challenged; for instance, in California, a Low-Carbon Fuel Standard (LCFS) has fundamentally altered this conventional interpretation to reflect the climate implications of products [77]. However, as in the hydrogen field, the traditional interpretation has been prevalent, despite the IRENA report having warned that "fossil CCS investments may divert limited capital away from renewable energy deployment back to fossil fuels" [2] (p. 16).

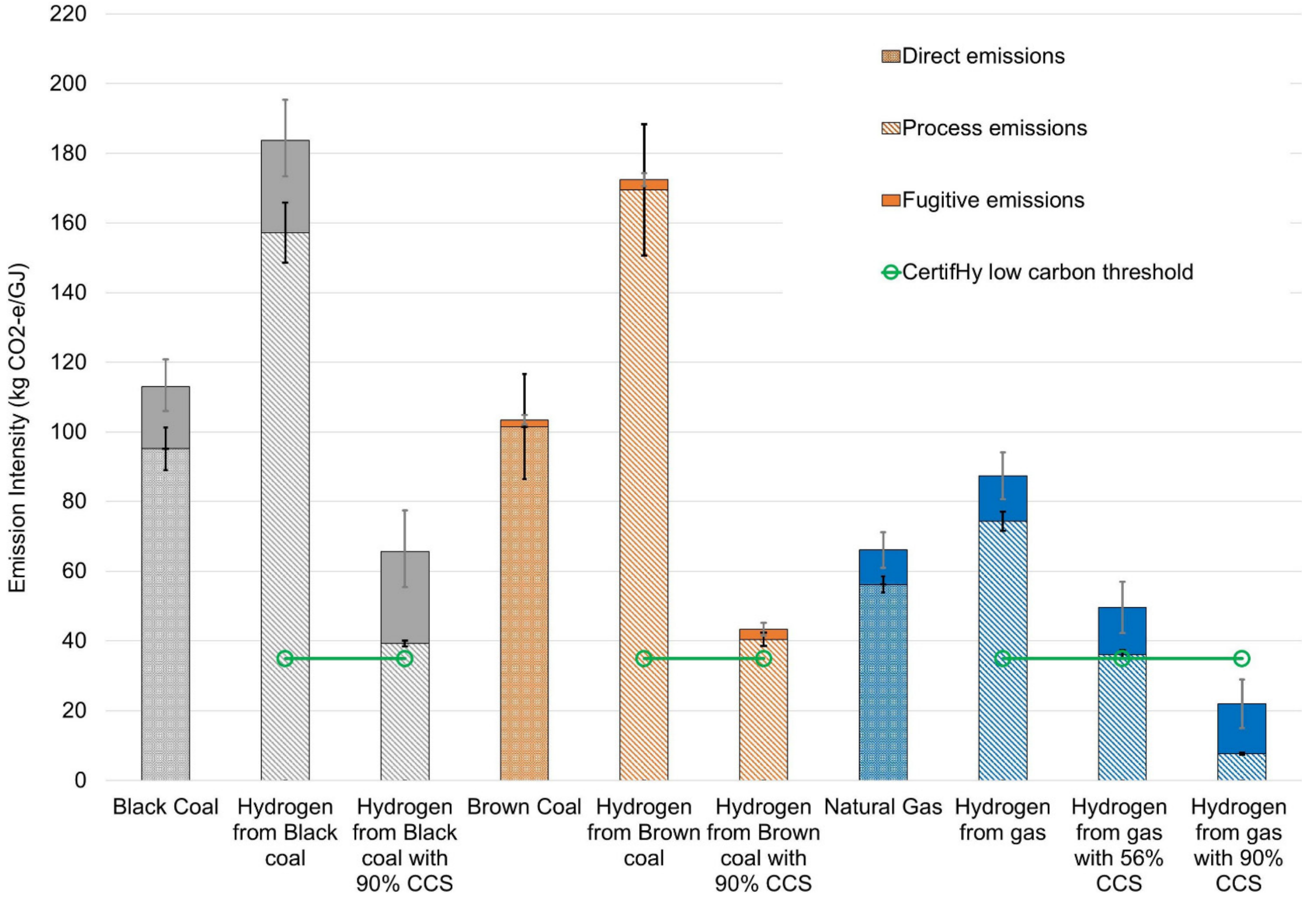

Figure 2. Total emissions intensity of different fuels, including direct emissions from the combustion of brown/black coal and natural gas, process emissions associated with the production of hydrogen from these fossil fuels, and fugitive emissions from fossil-fuel extraction [10] (p. 3).

We do not intend to judge which interpretation is better or how the current interpretation of technology neutrality in national hydrogen strategies can be improved; instead, our analysis focuses on whether the principle of technology is mentioned and implemented according to a national hydrogen strategy's own interpretation. According to the literature [9] (p. 10), it suffices to assume that, when advocating its support for technology neutrality, a national hydrogen strategy would equally enable innovations of renewable hydrogen and other types of fossil-fuel-based hydrogen defined by the strategy. Therefore, it would not be considered as "green hydrogen specific innovation enablement". We note that some national strategies do not mention the technology neutrality principle. In these cases, we refer to the text to determine whether the principle is implied or whether innovation support is dedicated to green hydrogen.

The three regulatory measures are established as general practices for countries. In addition to the three measures, there are fewer common regulations, such as blending obligation in the EU, i.e., demanding an obligation for blending green/low-carbon hydrogen defined in respective hydrogen strategies into the natural gas grid. In countries like Japan and India, renewable energy purchasing obligations are also introduced [78,79]. In the US, the "Green Book" for tax credit has defined low-carbon hydrogen eligible for the credit as hydrogen produced from nuclear energy or renewable energy or using natural gas where the carbon byproduct is captured and sequestered. However, as these measures do not commonly exist in most other countries' hydrogen strategies, we do not further analyze them in our study.

2.3. Typology for Green Hydrogen Regulatory Stringency

The concept of regulatory stringency reflects the degree to which regulation is implemented to achieve the objectives [80]. The concept has developed in the governance and regulation discipline to assess the comprehensiveness, prescriptiveness, and enforcement levels of regulation which may further have an impact on trust, legitimacy, compliance costs, and adoption [81]. Despite it being difficult to measure (environmental) regulatory stringency because of multidimensionality, simultaneity, and other challenges [82], Judge-Lord et al. [81] suggested that two thematic proxies for measuring regulatory stringency have been continuously mentioned by scholars, which are "scope" and "prescriptiveness". "Scope" decides a regulation or policy's full range of issues that it may cover, focusing on the policy settings or specific requirements of the issues. "Prescriptiveness" occurs on a continuum, versus "flexibility", and it measures the extent of the mandatory requirements or substantive thresholds that the regulation or the policy imposes. Notably, a third dimension—how the requirements are enforced—while being recognized as an important dimension of regulatory stringency [83] (p. 281), is often treated as a separate issue by the literature [81] (p. 102). This paper does not investigate the implementation in detail for another two practical reasons. First, most of the national hydrogen strategies aim to set the agenda and frameworks for hydrogen regulation; hence, there is a lack of detailed information about how the agenda is implemented within the strategies. Secondly, considering that most national hydrogen strategies were issued in 2020 and 2021, it is difficult to assess implementation within such a short timeframe.

In this study, we focus on regulatory stringency for green hydrogen in national hydrogen strategies, rather than the hydrogen economy in general. This means that how green the national hydrogen strategies are (our central research question) is different from how green a country's hydrogen production is in reality. Nonetheless, these are related questions, because national hydrogen strategy as a type of national industrial strategy [84] is essential to set rules that affect domestic marketplaces to guide the hydrogen industry to develop in an envisaged direction.

Our framework of regulatory stringency for green hydrogen takes into consideration the scope and prescriptiveness by examining the extent to which national hydrogen strategies are designing or implementing regulations toward producing hydrogen with zero embedded carbon emissions (renewable hydrogen). We only consider regulations to be stringent when they promote zero-carbon renewable hydrogen. This is because it is clear from climate science that emissions from fossil-fuel-based hydrogen production could be "substantial" even with CCS technology [10].

We set up a framework of typology to measure green hydrogen regulatory stringency in national hydrogen strategies (Figure 3). It has four parameters, including one temporal parameter of green hydrogen uptake and three regulatory parameters. The temporal parameter assesses countries' hydrogen strategies according to their readiness for green hydrogen in a temporal manner, focusing on "when a hydrogen strategy is/will be committed to green hydrogen". It is the parameter deciding the first-level categorization, differentiating national hydrogen strategies into three groups, namely, "zero regulatory stringency (not committed)", "scale first and clean later" (in the future), and "green hydrogen now (now)". Zero regulatory stringency represents countries with national hydrogen strategies that do not have any intention to create special regulations to support green hydrogen. Scale first and clean later includes countries with national hydrogen strategies that have one or more green hydrogen regulatory measures in place. They take an industry-expansion approach in which fossil-fuel-based hydrogen is deployed at least in the short term. These countries are aware of climate objectives via hydrogen but take an incremental transitional pathway. The zero regulatory stringency group is differentiated from the groups of scale first and clean later and green hydrogen now in that no regulation exists in the first group to differentiate renewable (green) hydrogen from fossil-fuel-based hydrogen. Most of the countries have set decarbonization targets in the proximal future but are trying to expand the use of fossil-fuel hydrogen to maximize their hydrogen economy potential. When all regulations in a scale first and clean later approach are in place, it is further examined by the temporal measure when they will be implemented: if in the future, a country stays in the scale first and clean later group; if implemented now, it is in the green hydrogen now group. In other words, the green hydrogen now group includes countries implementing all three regulatory measures now.

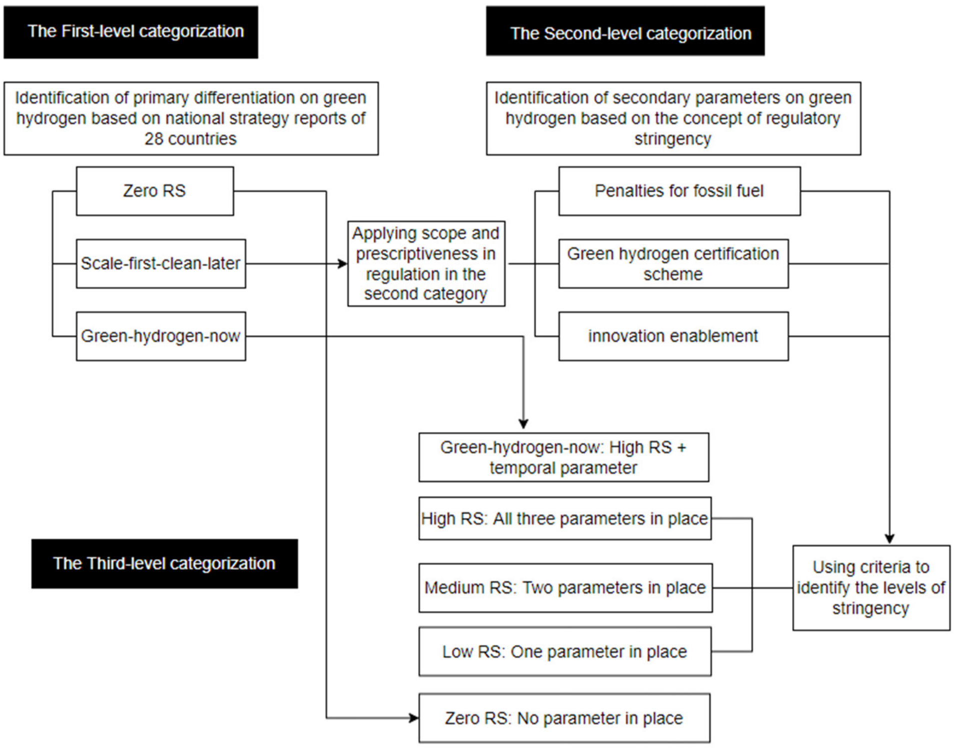

Figure 3. Categorization process for the framework. RS = regulatory stringency.

A resilient green hydrogen future needs to have zero carbon emissions. We identified three major regulations that are widely adopted in national hydrogen strategies: discouraging fossil-fuel hydrogen (fossil-fuel penalties), differentiating hydrogen produced with varied embedded carbon emissions (certification), and exclusive support for renewable hydrogen technologies (green hydrogen enablement). As mentioned, except for the zero regulatory stringency group, there are some regulatory measures in place to support green hydrogen. We analyze these regulations and use them as parameters to assess "whether a hydrogen strategy established selected regulatory measures and how".

The second-level categorization is created to divide national hydrogen strategies by the above three regulatory parameters, (focusing more on scope than prescriptiveness. Fossil-fuel penalties discourage the most emissions-intensive fossil-fuel hydrogen produced from coal gasification. However, we acknowledge that this is a second-best option because countries do not directly mention in their hydrogen strategies specific timelines for phasing out fossil-fuel-based hydrogen. Certification schemes include the guarantee of origins and renewable energy/gas certification in general that can differentiate between hydrogen types on the basis of their emission intensities and inform other market players with labeling [9,69]. The last parameter is exclusive innovation enablement for renewable hydrogen. For this parameter, we consider two factors; the first is the stance of equally supporting all hydrogen technologies (often based on the principle of technology neutrality) [8]. If there is no such technology-neutral declaration, we further examine whether support for innovation is directed to renewable hydrogen technologies. The establishment (in some cases, development) of these three regulatory measures enables us to interrogate the extent to which the national hydrogen strategies are committed to decarbonization instead of merely giving credit to ambiguous claims on clean or low-carbon hydrogen.

We use binary criteria to code regulatory parameters at the second-level categorization (Table 1). It is counted as "yes" when a regulatory measure already exists or when there is substantial evidence that regulation in preparation will be implemented very soon. Otherwise, it is counted as "no". As discussed above, the parameters of fossil-fuel penalties and innovation enablement involve two criteria; fossil-fuel penalties are assessed by both coal phasing out timelines and carbon pricing. Only when both regulatory measures are in place can the overall fossil-fuel penalties criteria be satisfied. Exclusive green hydrogen innovation enablement requires assessment where (1) the principle of technology neutrality is not supported or mentioned, and (2) there is evidence in the national hydrogen strategy or other supporting documents that innovation enablement is directed solely to renewable hydrogen. Again, both requirements need to be satisfied to be counted as "yes". The overall coding is presented at the end of Section 3.

Table 1. The framework of regulatory stringency for green hydrogen.

Zero Regulatory Stringency	Scale-First-and-Clean-Later		Green-Hydrogen-Now
	Penalties for fossil fuel	Coal phasing-out timeline	
		Carbon pricing	
	Hydrogen certification scheme		
	Innovation enablement	Disapproval of technology neutrality	
		Exclusive support for renewable hydrogen *	

* Investment or targeted funding/grants for green hydrogen, and direct support for green hydrogen innovation such as electrolysis.

The third-level categorization is both a refinement of the second-level categorization and the combination of the temporal parameter and the regulatory parameters. In terms of refinement, the central consideration for the third-level categorization is "how many regulatory measures are adopted in a national hydrogen strategy". This is based on the results of the binary coding of the second-level categorization. As indicated in Figure 3, the results are further disaggregated into three levels: low regulatory stringency group including national hydrogen strategies with one regulatory parameter, medium regulatory stringency group including strategies with two regulatory parameters in place, and high regulatory stringency group with all three regulatory parameters in place. These refined results can be further combined with the temporal consideration. In this case, zero regulatory stringency means a national hydrogen strategy has not established any of the regulations and is not committed now. More importantly, the combination of temporal and regulatory measures distinguishes the high regulatory stringency and green hydrogen now. The high regulatory stringency level includes national hydrogen strategies having all three regulatory parameters in place, but the coal phasing-out timeline is set in the future. Green hydrogen now covers national hydrogen strategies that have all three regulatory parameters in place and the temporal parameter met (coal has already been phased out).

3. Results

As indicated in the research design, the second-level categorization is the key to examining regulatory stringency. We present our findings on whether the national hydrogen strategies have adopted these regulatory measures and how in this section. A binary coding of the results is summarized at the end of this section. The outcome of the third-level categorization is further discussed in Section 4.

3.1. Fossil-Fuel Penalties

Phasing out coal from the electricity sector is the single most important step to get in line with 1.5 °C of the temperature goal [85]. To reach net zero by 2050, countries need to rapidly phase out coal (by 2030 in EU/OECD, 2037 in non-OECD Asia, and 2040 in the rest of the world) [85]. As hydrogen produced from coal gasification has the highest carbon emissions intensity (Figure 1), we use coal phasing-out timelines as a proxy indicator to reflect the regulatory stringency for hydrogen to reach decarbonization goals. This indicator is also selected because, despite most hydrogen currently being produced from natural gas, no country in the world has committed to phasing out fossil-fuel energy sources beyond coal (while acknowledging that COP 26 outcomes include a pledge to cut methane). Taking into account carbon removal factors, through carbon capture and storage (CCS), for instance, many countries have announced carbon neutral or net-zero emissions targets as their nationally determined contributions to implement the Paris Agreement [60]. While the net-zero targets announced by over 60 countries may indicate a turning point for global climate governance, the coal phasing-out timeline we adopt in this study is a more rigorous criterion.

Countries such as Canada, Denmark, France, Hungary, Italy, the Netherlands, Portugal, Slovakia, and the UK have coal phase-out targets by 2030 or earlier. Germany follows with a coal phase-out timeline of 2038, and Poland recently pledged to quit coal by 2049. Among the EU members states that have issued their national hydrogen strategies, the Czech Republic is not yet come up with a timeline, but coal phasing out is under consideration with 2038 as the latest exit year. Poland has recently announced that it will try to keep its state-owned coal mining company, PGG, operating until 2049 using state aid despite the apparent divergence from the EU's goals and directions. A number of countries do not yet have plans to quit coal, including Australia, Colombia, India, Japan, Morocco, Paraguay, and the US, despite most of them having made net-zero pledges. Table 2 shows whether a coal phasing-out timeline and carbon pricing are in place in countries that established national hydrogens strategies and how they are implemented.

Table 2. Detailed analysis on fossil-fuel penalties.

Country	Coal Phase-Out Timeline Indicated	Year	Carbon Pricing	Notes
Australia	No		No	The Australian national hydrogens strategy intends to develop "clean hydrogen", which includes hydrogen produced using renewable energy or using fossil fuels with substantial CCS. While this definition in a way restrained fossil-fuel-based hydrogen without CO_2 removal, there are no external fossil-fuel penalties beyond the strategy.
Canada	Yes	2030	Carbon tax, ETS implemented	The federal and provincial governments are "committed to negotiating" a new or amended deal for the period 2015–2040 Canada Nova Scotia equivalency agreement regarding greenhouse gas emissions from electricity producers, 2020. - Promising not to commit any new finance for unabated coal, oil, and gas projects in other countries by the end of 2022.

Table 2. *Cont.*

Country	Coal Phase-Out Timeline Indicated	Year	Carbon Pricing	Notes
Chile	Yes	2040	Carbon tax implemented, ETS under consideration	- The Plan de Retiro del Carbón (Coal Phase-Out Plan), to combat climate change and achieve carbon neutrality by 2050. - The Government committed in 2019 to close all of Chile's coal-fired power plants by 2040. - In July 2021, Minister Jobet announced the closure of all coal-fired power plants in Puchuncaví and 80% of those in Mejillones by 2025.
Colombia	No		Carbon tax implemented, ETS under consideration	Net zero by 2050 pledged.
Czech Republic	Yes	2038	EU ETS	- A multi-stakeholder coal commission was established to assess the possibility of a coal phase out which recommended a 2038 coal exit, but the government is considering an earlier date.
The EU	Yes	2030	ETS implemented	- The EU climate law has set carbon neutrality by 2050 as a legal obligation. - Coal has been in sharp decline in the EU since 2012. The EU's new climate ambitions for 2030 and 2050 and the upcoming changes to the EU Emissions Trading System are expected to accelerate the coal phase out.
Finland	Yes	2029	Carbon tax implemented	- Aim to achieve carbon neutrality by 2035 as the first industrial country in the world. - Create an incentive program to increase demand for clean hydrogen and its byproducts (e.g., carbon contracts for difference). Focus on creating hydrogen hubs by 2022. - Nominate a national body for wind power and hydrogen permitting coordination by 2021.
France	Yes	2022	Carbon tax implemented	- As all but one of the French coal plants have announced closure by 2022, this concerns the Cordemais plant for which there are plans to co-fire it with biomass.
Germany	Yes	2038 (possibly 2035)	ETS implemented	Banned the starting of new coal-fired plants after 14 August 2020; the coal plant who received the license to operate until the date will be allowed to operate until 2038.
Hungary	Yes	2025	ETS implemented	The coal phase-out date has recently been moved 5 years earlier than originally announced, to 2025 instead of 2030.

Table 2. *Cont.*

Country	Coal Phase-Out Timeline Indicated	Year	Carbon Pricing	Notes
India	No		No	- Coal makes up more than 50% of India's installed electricity generation capacity and the country also possesses the fourth-largest global reserves of the mineral. - New coal power plants should be built on the condition that they are able to capture and store their carbon emissions. - Net-zero emissions by 2070 to secure 50% of India's energy from renewable resources by 2030.
Italy	Yes	2025	EU ETS	- Promising not to commit any new finance for unabated coal, oil, and gas projects in other countries by the end of 2022.
Japan	No		Carbon tax implemented	- Announced immediate stop of state-backed overseas coal financing in 2021. - Japan does not pledge for coal phasing out at COP 26 [86].
Morocco	No		No	- Morocco partly supported the COP26 Coal to Clean Power Transition Statement. However, it only agreed to no new coal, without a timeline for coal phasing out [87].
The Netherlands	Yes	2029	Carbon tax implemented	- Several major utilities such as RWE and Uniper have invoked the Energy Charter Treaty, a legally binding multilateral agreement aimed toward cross-border cooperation in the energy industry, to sue the Netherlands for more than two billion USD as compensation for phasing out coal power by 2030.
New Zealand	Yes	2030s	ETS implemented	- Agreeing to stop providing public finance for oil, gas, and coal projects abroad by 2022.
Norway	No		Carbon tax implemented	- It is reported that Norway's state-owned coal company will close its last mine in the Arctic Svalbard archipelago in 2023 [88]. However, the Norwegian government does not make any official announcement for coal phasing out. - No target date set for net-zero emissions.
Paraguay	No		No	- No target date set for net zero.
Poland	Yes	2049	Carbon tax implemented	- It has been criticized that the 2049 phasing-out timeline is not consistent with the EU's overall commitment of coal phasing out [87]. - No target date set for net zero.
Portugal	Yes	2021	Carbon tax implemented	- Net zero by 2050 pledged. - Operator of the country's last coal plant closed in November 2021 [89], making Portugal the fourth EU member state that have quit coal.
Republic of Korea	Yes	2030	ETS implemented	- Net zero by 2050 pledged. - Announced immediate stop of state-backed overseas coal financing in 2021.

Table 2. *Cont.*

Country	Coal Phase-Out Timeline Indicated	Year	Carbon Pricing	Notes
Russia	No		No	- Net zero by 2060.
Slovakia	Yes	2030	EU ETS	- Net zero set by 2050.
Spain	Yes	2030	Carbon tax implemented	- Net zero by 2050. - Spain will be coal power-free by the mid-2020s. - Carbon tax introduced.
Ukraine	Yes	2035	Carbon tax implemented, ETS under consideration	- In the first week of COP26, Ukraine joined the Powering Past Coal Alliance (PPCA) and pledged that it will stop burning coal by 2035 [90]. - Net zero by 2060.
The UAE	No		No	- Net zero by 2050. - A leader in the Middle East with the first solar-driven hydrogen electrolysis facility under construction at Hatta.
The UK	Yes	2024	Carbon tax, ETS implemented	- Pledged not to commit any new finance for unabated coal, oil, and gas projects in other countries by the end of 2022.
The US	No		10 states participated in RGCI, but no national carbon pricing	- Promising not to commit any new finance for unabated coal, oil, and gas projects in other countries by the end of 2022. - Net zero by 2050.

Sources: Official documents on climate actions including carbon neutrality and quitting coal, COP26 outcomes, and World Bank data on carbon pricing [91–95].

Recent climate deals at the COP 26 in Glasgow have revealed countries' political will to pursue a path toward phasing out coal and cut methane. Twenty-three countries have committed themselves to stop constructing or issuing permits for new coal plants. More than 40 countries, including Canada, Chile, Germany, Hungary, Italy, the Netherlands, New Zealand, Poland, Portugal, Slovakia, South Korea, Spain, and the United Kingdom, have pledged to quit coal. India has not participated due to the country's agenda for poverty eradication, but new coal power plants should be built on the condition that they are able to capture and store their carbon emissions. Canada, South Korea, the UK, and the US have agreed to stop overseas coal financing.

In relation to hydrogen, coal phasing out is an important step, but may not be sufficient for a rapid transition. For instance, the tolerance of "low carbon" until 2030, declared by the EU, has raised significant concerns [96]. Camile Maury at the WWF Europe criticized that, by "low-carbon", the EU is endorsing hydrogen produced by gas with carbon capture and storage, which would give "a free pass to new gas which would completely undermine the EU's climate neutrality target" (webpage, no page number). Furthermore, effects on overall water pollution and biodiversity due to the production of hydrogen have not been considered [97].

Another criterion for penalties for fossil fuel is carbon pricing. Carbon pricing and measures to reduce carbon emissions, including instituting environmental regulations, ETS, and carbon taxes, have been widely adopted by countries worldwide. ETS caps the total level of greenhouse gas emissions and allows industries with low emissions to sell their extra allowances to larger emitters by creating a market price for greenhouse gas emissions. A carbon tax sets a predefined price on carbon, thereby regulating emissions reduction outcomes. All member states of the European Union are part of the EU Emissions Trading System (EU ETS), a market created to trade a capped number of greenhouse gas emission allowances. Italy joined the EU ETS in 2017. Following Brexit, the UK implemented its own UK ETS as of January 2021.

Since the EU ETS in 2005, there have been various developments worldwide. This trend has reached other parts of the world. New Zealand has adopted an ETS. In Korea, there have been discussions on introducing a carbon tax, but there has not been a resolution. Korea adopted its first nationwide ETS scheme in 2019. In the US, 10 states in the northeast implemented the Regional Greenhouse Gas Initiative (RGGI) in 2009, but there is no national wide carbon pricing mechanism.

3.2. Certification Schemes

Certifications are third-party voluntary regulations that many national hydrogen strategies mention to differentiate between types of hydrogen, trace embedded carbon emissions, and channel renewable hydrogen with existing renewable energy credit schemes. The defining characteristics of "green", "clean", or "low-carbon" hydrogen are often set through certification schemes. However, having a certification scheme does not automatically guarantee environmental objectives, which further depend on the stringency of the certification, including emission thresholds and carbon accounting system boundaries. While the threshold for renewable hydrogen needs to be zero emissions, the volumes of emissions that would qualify hydrogen as low-carbon or clean hydrogen are at the discretion of certifying organizations. They may consider multiple factors beyond environmental ones to set the threshold, including the competitiveness of their hydrogen industry internationally, market demand, and transitional timelines. For instance, in New Zealand, the arguments for and against a low-carbon hydrogen certificate were presented, and it is recognized that a threshold for low-carbon certificates should be as stringent as possible, without limiting the potential for emissions displacement [98] (p. 4). Carbon accounting system boundaries (Figure 4) also impact carbon emissions of certifications [70]. As demonstrated, only the German TÜV SÜD adopts the cradle-to-grave carbon emissions scope; most hydrogen certificates have adopted less stringent cradle-to-gate boundaries. We also acknowledge the importance of private regulation through certifications; therefore, this study covers private industry-led hydrogen certifications as an implementation of a national hydrogen strategy. While noting that the Aichi Prefecture in Japan and California in the US have established subnational hydrogen certification schemes, these certifications are outside of the scope of this paper.

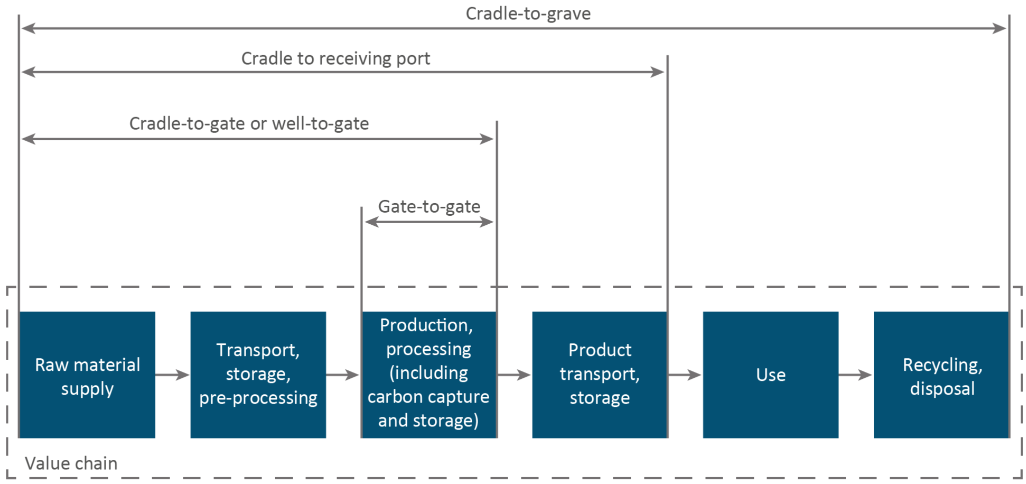

Figure 4. Hydrogen carbon accounting system boundaries [70].

When combining the factors of different terminologies adopted to classify hydrogen, associated with their carbon emission thresholds (in most cases, for low-carbon or clean hydrogen) and carbon accounting system boundaries, the certification systems are difficult to be compared with each other (Table 3).

Table 3. Hydrogen certification schemes in national hydrogen strategies.

Country	Status	Certifying Body	Hydrogen Label with Eligible Production Methods	Emissions Threshold	Carbon Accounting System Boundaries	Offset
Australia [18,71]	In development	TBC	**Clean hydrogen** from three main production pathways: electrolysis, coal gasification with CCS, and steam methane reforming with CCS.	TBC	TBC	Possible
Australia [99]	In operation	Smart Energy Council	**Zero-carbon hydrogen** certification for renewable hydrogen	n/a	n/a	n/a
Canada [19]	In development					
Chile [20]	In development	Possibly mirror CertifHy	Green hydrogen	TBC	TBC	TBC
Colombia [21]	In development					
Czech Republic [22]	In development	MIT	**Certification for low-carbon hydrogen** according to CO_2eqv., regardless of its production method	Maximum of 36.4 g CO_2eq/MJ_{H2}	TBC	TBC
The EU [9,23]	In operation	CertifHy (Phase III)	**CertifHy green hydrogen** produced through electrolysis powered by renewables such as solar, hydro, wind, and biogas **CertifHy low-carbon hydrogen** produced from nonrenewable low-carbon source	Emissions below 70% intensity of hydrogen produced from natural gas, at 24.5 g CO_2e/MJ_{H2} (previously 60% in CertifHy Phase II at 36.4 g CO_2eq/MJ_{H2})	Well-to-gate	No
The EU [100]	In operation	REDII	**Renewable transport fuels of nonbiological origin**	70% reduction as compared with Baseline	Not specified	No
Finland [24]	Not mentioned					
France [25]	In operation	AFHYPAC	**Green hydrogen** produced from all renewable pathways	100% renewable	Not specified	No
Germany [101]	In operation	Clean Energy Partnership	**Green hydrogen** produced from electrolysis and biomass	100% electricity from renewables	Cradle-to-gate	No
Germany [102]	In operation	TÜV SÜD (Version 01/2020)	**Green hydrogen** produced from renewable energy sources **Nonrenewable low-carbon hydrogen**	For low-carbon hydrogen, 75% GHG reduction potential 60% GHG reduction potential if used for transport; or 50% reduction potential for other use	Cradle-to-grave	No
Hungary [27]	In development (applying the EU standards directly)	TBC	Various hydrogen types: green (renewable) hydrogen, other carbon-free hydrogen, and low-carbon hydrogen	TBC	TBC	Possibly no
India [28,29]	Not mentioned					
Italy [103] [104]	In development (to be aligned with EU directives)	TBC	**Renewable hydrogen. Low-carbon hydrogen**	TBC	TBC	TBC
Japan [101]	In development	Japan will consider institutional designs that ensure hydrogen power generation's economic efficiency. It is important to visualize the environmental value of hydrogen power generation in terms of assessment, certification, and trading [31].				
Morocco	In development	Morocco co-facilitated IRENA's Collaborative Framework on Green Hydrogen to develop certification of the green hydrogen and commodities [105,106] Moroccan Ministry of Energy, Mines, and Environment will experiment a pilot cross-border GO transaction with the EU's CertifHy III [107]				

Table 3. *Cont.*

Country	Status	Certifying Body	Hydrogen Label with Eligible Production Methods	Emissions Threshold	Carbon Accounting System Boundaries	Offset
The Netherlands [33]	In development (Agreements with CertifHy)	Vergogas				
New Zealand [34]	In development	Certified Energy	Renewable gas certification for green hydrogen Low-carbon gas certification may also be available	100% renewable	TBC	TBC [98]
Norway [35]	No	Although the strategy mentioned the term certification, it is used in the context of aviation (certify electrified planes) and the safety of using hydrogen in shipping These certifications are not green hydrogen certification discussed in this section				
Paraguay [36]	No					
Poland [37]	No					
Portugal [38,39]	In development	EEGO	Gases of renewable origin for green hydrogen and low-carbon gases			
Republic of Korea [40]	In operation		Extending renewable energy certificates (RECs) to renewable hydrogen	100% renewable	TBC	TBC
Russia [41]	In development					
Slovakia [43]	In development					
Spain [44]	In development Guarantees of Origin (to be aligned with EU standards)	MITECO	Renewable gases including renewable hydrogen, biogas, and any other renewable gas	100% renewable	Possibly cradle-to-gate	
Ukraine [45]	In development (taking into account European standards and norms)	TBC	Hydrogen from renewable energy sources			
The UAE	In development	Department of Energy emphasized certifications as part of the UAE's hydrogen regulatory framework [108] UAE and Germany also agreed to establish a trustworthy certification scheme to ensure that sustainability criteria are met [109]				
The UK [48,110]	In development	Department for Energy and Climate Change (DECC)	**Low-carbon hydrogen**: single label that can be applicable to all production methods that meet the GHG threshold	TBC	Possibly cradle-to-gate	
The US [49]	No					

Note: TBC = criteria to be confirmed; n/a = information not available. Sources: national hydrogen strategies, implementing regulations of the strategies while available, and relevant reports [3,9,11].

Nonetheless, partial coordination among some hydrogen certifications is achieved in two ways. In the EU, the development of a GO system is required by the Renewable Energy Directive (RED II). Therefore, many EU member states seek to align their GOs with the EU-wide CertifHy. For instance, the German TÜV SÜD green hydrogen can be registered under the EU-wide CertifHy scheme to facilitate compatibility for producers and users. However, it is not clear how German cradle-to-grave carbon accounting is channeled with CertifHy's cradle-to-gate in this registration. The Dutch hydrogen strategy also states that their development of the GO system will aim to implement European rules and measurement methodology as much as possible. Secondly, as hydrogen is and will be internationally traded, export counties such as Australia have actively sought to align their hydrogen certification with that of Germany [111]. This is exactly the recommendation provided by a German consulting firm and World Bank for Chile; acknowledging that the definition of green and sustainable products is often set by the importing market on the basis of their priority sustainability criteria, the Chilean hydrogen certification scheme should begin by understanding the applicable definitions in the target markets, in particular the EU, and adopting CertifHy directly [112]. Moreover, CertifHy also has extended its pilot to non-European countries like Morocco. Poland, whilst an EU member state, does not mention how CertifHy could be channeled in its national hydrogen strategy, and conventional hydrogen produced mainly from natural gas is its immediate focus [37,50]. The Republic of Korea has extended its existing tradeable certificate scheme, Renewable Energy Certificates, to cover renewable hydrogen. Portugal and New Zealand's certifications cover renewable gases including hydrogen. New Zealand's certification also covers biomethane.

Some export-oriented countries do not include a hydrogen certification scheme in their national hydrogen strategies, yet the entire hydrogen strategy still refers to green hydrogen, such as the strategy of Paraguay. It has been reported that the British company Atome Energy PLC is fully engaged with hydrogen production in Paraguay through the electrolysis of water, and Paraguay aims to be the largest hydrogen producer in the world [113]. The upscaling of renewable hydrogen through FDI and guaranteed export destination may render certification unnecessary. Nonetheless, certification could still enhance transparency, in particular for carbon accounting purposes, to guarantee that the electricity used for producing hydrogen is from renewable sources. For the UAE, the Dubai Electricity and Water Authority (DEWA) has inaugurated green hydrogen in Hatta. Despite the project being celebrated as "the first of its kind" in the Middle East and North Africa to produce green hydrogen, it has not yet mentioned adopting any certification scheme.

3.3. Innovation Enablement

The innovation enablement parameter looks at two factors: (1) whether the term technology neutrality is expressed in a national hydrogen strategy, and (2) if not, whether innovation and associated infrastructure support are exclusively allocated to renewable hydrogen (Table 4). This contextual approach to technology neutrality (the second factor) is taken because even if the exact term "technology neutrality" may not appear in a national hydrogen strategy, the strategy may still support the deployment of fossil-fuel technologies.

Table 4. Detailed country analysis on renewable hydrogen enablement.

Country	Technology Neutrality Mentioned	Major Initiatives Supporting Renewable Hydrogen
Australia	Yes	The renewable hydrogen will be produced by a 220 KW electrolyzer, which will be powered by onsite solar, or grid-sourced renewable energy.
Canada	Yes	- 20 MW electrolyzer plant in Becancour, projects developing in BC to support hydrogen fueling network.
Chile	No	- Have 5 GW of electrolysis capacity under development by 2025. - Produce the cheapest green hydrogen in the world by 2030. - Expand the deployment of green hydrogen projects in the short to medium term.
Colombia	Yes	- Develop between 1 and 3 GW of electrolysis capacity in regions with highly renewable resources such as La Guajira by 2030. - Produce at least 50 kT of blue hydrogen by capturing CO_2 in existing SMR plants or new plants for storage or use by 2030. - Export to other geographies with enhanced technological maturity by 2050.
Czech Republic	Yes	- Intends to focus on production of green hydrogen from renewable energy sources and has announced that it plans to develop six electrolyzer projects with a total capacity of 10 MW by 2025. - The development of systems for the pyrolysis decomposition of organic waste and natural gas, as well as the construction of large local solar or wind power plants connected to electrolyzers. - Hydrogen from renewable sources includes not only electrolysis of water; it can also be produced by biogas/biomethane reforming (instead of natural gas reforming) or by biochemical or thermochemical conversion of biomass. Hydrogen produced from nuclear power is part of the strategy.

Table 4. *Cont.*

Country	Technology Neutrality Mentioned	Major Initiatives Supporting Renewable Hydrogen
The EU	Yes	- Investment of 13 to 15 billion EUR until 2030 into electrolysis within the EU, and a further 50 to 150 billion EUR into renewable energy sources with an installed capacity of 50–75 GW. - By 2050, cumulative investments in renewable hydrogen could be 180–479 billion EUR, with 3–18 billion EUR for low-carbon fossil-fuel-based hydrogen. - Developed a plan to reach 2 × 40 GW of electrolyzer capacity by 2030. - Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.
Finland	No *	- Emphasizing the role of hydrogen produced from low-carbon sources, as well as with CCUS, is recognized [114].
France	Yes	- The aim is to develop "gigafactory" electrolyzer projects in France to increase electrolyzer capacity to reach 0.8–1 GW to produce decarbonized hydrogen.
Germany	Yes	- Plans to establish up to 5 GW of generation capacity including the offshore and onshore energy generation facilities.
Hungary	No *	- Acknowledges that the Paks nuclear power plant may supply a significant amount of carbon-free electricity for the establishment of a hydrogen value chain. - States the most cost-efficient solution for satisfying industrial demand for low-carbon footprint hydrogen is low-carbon "blue"/"turquoise" hydrogen. - Strategic timeline for 2030 established (16,000 t/year of "green" and other carbon-free hydrogen). - 240 MW electrolyzer capacity [27].
India	No *	- Acknowledges the need to put nuclear-powered hydrogen in the mix to aid the net-zero 2070 deadline [115]. - The renewable electricity tariffs are already among the lowest in the world. - Conducting bids for 4000 MW of electrolyzer capacity.
Italy	No	- The National Hydrogen Strategy is very explicit in targeting support to green hydrogen alone, i.e., that obtained by electrolysis fueled by renewable energy. - Anticipates the installation of approximately 5 GW of electrolysis capacity by 2030.
Japan	No *	- It is unrealistic to cover all electricity demand only with renewables, with "50–60% renewables in 2050" as a reference. - CCS and renewable energy technologies can be used to make hydrogen a completely-CO_2-free energy source. - Hydrogen produced from nuclear power is supported. - Japan's basic approach is to develop an international supply chain to reduce the cost of hydrogen include combining overseas unused energy with CCS and procuring massive amounts of hydrogen from cheap renewable energy.
Morocco	No	- Positioned to produce 4% of the global demand for green hydrogen. Tender for a 100 MW green hydrogen electrolyzer project in 2022, aiming to be operational by 2025. - Agreement being signed with Germany that would see an industrial-scale green ammonia plant built in Morocco. - Morocco also established bilateral relationships for green hydrogen with Chile, Portugal, IRENA.

Table 4. *Cont.*

Country	Technology Neutrality Mentioned	Major Initiatives Supporting Renewable Hydrogen
The Netherlands	No *	- An ambition to scale up electrolysis to approximately 500 MW of installed capacity by 2025 and 3–4 GW of installed capacity by 2030. - A new support scheme for cost-effective carbon emissions reduction (the SDE++) will provide sufficient support for blue hydrogen projects with CCS.
New Zealand	No	- 50 GW of announced green hydrogen electrolyzer projects through to 2030. - Clear timeline indicated to completely transition to renewable hydrogen.
Norway	No *	- Hydrogen from steam-reforming processes involving natural gas or other fossil fuels combined with CCS included. - Projects under development with electrolysis plants of 10 MW or more.
Paraguay	No	- Promote the manufacture and development of electrolyzers and technologies associated with the use of green hydrogen using the country's abundant hydropower.
Poland	No *	- 50 MW and 2 GW of electrolyzer capacity is planned to be integrated in the energy value chain by 2030 and 2040 accordingly. - Assumes the use of electricity from nuclear power plants to produce hydrogen.
Portugal	No	- 2 GW installed capacity in electrolyzers by 2030. - Aims to develop as an important hub of green hydrogen.
Republic of Korea	No *	- Gray, blue, and green hydrogen projects are being considered. - Develop MW-class, renewable energy-linked water electrolysis design technology by 2022 and demonstrate 100 MW-class renewable energy-linked technology.
Russia	Yes	- Primarily aims to develop production capacities in hydrogen produced from nuclear power and from natural gas [116]. - Technology neutrality is used to safeguard hydrogen produced from fossil fuels and nuclear power [42].
Slovakia	Yes	- Aims to utilize low-carbon footprint energy mix due to the big share of nuclear power generation and large hydro power plants. Big potential in well-developed gas infrastructure.
Spain	No	- Installed capacity of 4 GW electrolyzers and a series of milestones in the industrial, mobility and electricity sectors, for the period 2020–2030.
Ukraine	Yes	- Goal of 5 GW, planned for 2030, will need 20 TWh of renewable energy. - National Hydrogen Program: development of the concept of production and use of "brown", "gray", "blue", and "green" hydrogen by 2050.
The UAE	No *	- A detailed strategic assessment of the economic potential for green/blue/brown hydrogen with the time horizons 2030 and 2050. - A leader in the Middle East with the first solar hydrogen electrolysis plant under construction in Dubai and a fledgling fuel cell electric vehicle (FCEV) fleet [117].
The UK	Yes	The government aims to replace up to one-fifth of natural gas with "green" hydrogen, made through electrolysis powered by renewable energy.

Table 4. *Cont.*

Country	Technology Neutrality Mentioned	Major Initiatives Supporting Renewable Hydrogen
The US	No *	- Hydrogen from natural gas is commercially viable today and it could be a bridge technology with CCUS to enable future energy scenarios where hydrogen is sustainably produced using all of the diverse domestic resources. It needs to reduce capital costs and improve the efficiency of these technologies to be competitive. - A 5 MW electrolyzer project planned in Washington State, first-of-a-kind nuclear-to-hydrogen projects in multiple states, and a 20 MW electrolyzer plant to produce hydrogen from solar power in Florida.

* The absence of the wording "technology neutrality" does not necessarily mean a country is supporting green hydrogen solely. We refer to the second indicator of evidence for exclusive support for renewable hydrogen. Sources: National Strategies on hydrogen unless otherwise indicated in the table.

The EU and most EU member states adopt "technology neutrality" or "tech-neutral" approaches, except for Italy, Portugal, and Spain. Chile, Paraguay, and New Zealand do not support this principle either. While Italy does emphasize in its hydrogen strategy that green hydrogen will be promoted, it still lacks a regulatory framework that distinguishes and incentivizes small-scale hydrogen production from renewables. Portugal and Spain are currently developing sites for industrial production of renewable hydrogen and aim to become important hydrogen hubs in Europe. Chile aims to produce the cheapest green hydrogen in the world by 2030. Paraguay foresees great potential for green hydrogen based on its hydropower capacity. We note that EU member states that received the EU's COVID-19 recovery funds, including Italy, Spain, and Portugal, may spend the funds on CCS and "blue" fossil-fuel hydrogen. For instance, Italy's National Recovery and Resilience Plan is not explicit whether fossil-fuel hydrogen production with CCS will also be funded. In this study, we do not consider the EU and its members' COVID-19 recovery funds as part of the implementation of an EU member state's national hydrogen strategy. Our primary focus is on the strategies' position on innovation enablement instead of additional related initiatives after the launch of the strategies. However, in reality, this does pose the question of the dimension of implementation in regulatory stringency.

There are internal variations among countries supporting the principle. France and the UK clearly mention in their strategies that, despite the principle of technology neutrality, they put special emphasis on green hydrogen. The Czech Republic and Russia rely on this principle to justify their support for hydrogen produced from fossil fuels and nuclear power. In countries where the principle is not expressed, we further examine the allocation of supporting funds for hydrogen technologies. We found that, in Finland, Hungary, India, Japan, the Netherlands, Norway, Poland, Republic of Korea, the UAE, and the US, despite not using "technology neutrality" in the strategies, these countries support fossil-fuel hydrogen technologies and infrastructure in their hydrogen strategies.

Following a detailed analysis of each of the parameters, we present the combined results of regulatory stringency for green hydrogen in national hydrogen strategies in Table 5. We discuss the results in Section 4.1.

Table 5. Regulatory stringency parameters for green hydrogen by country.

	Zero Regulatory Stringency	Scale-First-and-Clean-Later			Green-Hydrogen-Now
		Hydrogen Certification	Renewable Hydrogen Enablement	Fossil-Fuel Penalties	
Australia		O	X	X	
Canada		O	X	O	

Table 5. *Cont.*

	Zero Regulatory Stringency	Scale-First-and-Clean-Later			Green-Hydrogen-Now
		Hydrogen Certification	Renewable Hydrogen Enablement	Fossil-Fuel Penalties	
Chile		O	O	O	
Colombia		O	X	X	
Czech Republic		O	X	O	
The EU		O	X	O	
Finland		X	X	O	
France		O	X	O	
Germany		O	X	O	
Hungary		O	X	O	
India	O	X	X	X	
Italy		O	O	O	
Japan		O	X	X	
Morocco		O	O	X	
The Netherlands		O	X	O	
New Zealand		O	O	O	
Norway	O	X	X	X	
Paraguay		X	O	X	
Poland		X	X	O	
Portugal		O	O	O	O
Republic of Korea		O	X	O	
Russia		O	X	X	
Slovakia		O	X	O	
Spain		O	O	O	
Ukraine		O	X	O	
The UAE		O	X	X	
The UK		O	X	O	
The US	O	X	X	X	

Note: O = yes; X = no. Renewable enablement and fossil-fuel penalties have two criteria. Both criteria need to be satisfied to qualify a "yes".

4. Discussion

4.1. Regulatory Stringency for Green Hydrogen in National Strategies

According to Table 5, we allocate countries into five different groups of regulatory stringency for green hydrogen (Table 6). As illustrated in Figure 3, the levels of regulatory stringency in the scale first and clean later group are associated with the number of regulatory measures in place.

The zero regulatory stringency group includes India, Norway, and the US. These countries intend to continue to rely on fossil-fuel resources and nuclear power plants to support hydrogen development. Without certification, consumers cannot tell the sources of hydrogen. Renewable hydrogen can only take the market when it is cheaper than fossil-fuel-based hydrogen, but this is difficult if not impossible without a nationwide coal phasing-out timeline or carbon pricing. Despite aspiring to become the world's largest green hydrogen exporter, India does not have any regulatory measures in place. However, the lack of a certification scheme, in particular, may impede the competitiveness of its green hydrogen in a global market, and there can be a high risk of green washing [118]. Norway is one of the world's largest exporters of natural gas and has not yet pledged to quit coal. It does not include any institutional design of hydrogen certifications despite its aspiration to engage in international maritime regulations of using hydrogen as a maritime fuel. CCS-related technologies have been its focus for innovation support. The US does not meet the parameters either, not because it does not have the regulatory capability, but because its predominant market-based regulatory approaches have constrained the use of more interventionist regulations such as carbon pricing nationally and exclusive support for renewable hydrogen. However, it is worth noting that many of the regulatory measures do exist in the US at the subnational level. Jurisdictions such as California have their own certifications and carbon pricing mechanisms that pioneer environmental regulation, known as the California effect [114]. Nonetheless, these subnational regulations do not count in this analysis.

Table 6. Identification of regulatory stringency for green hydrogen by groups.

Regulatory Stringency Groups		**Countries**
Zero regulatory stringency		India, Norway, the US
Scale-first-and-clean-later	Low regulatory stringency group	Australia, Colombia, Finland, Japan, Paraguay, Poland, Russia, the UAE
	Medium regulatory stringency group	Canada, the Czech Republic, the EU, France, Germany, Hungary, Morocco, the Netherlands, the Republic of Korea, Slovakia, Ukraine, the UK
	High regulatory stringency group	Chile, Italy, New Zealand, Spain,
Green-hydrogen-now		Portugal

The scale first and clean later group has three levels of regulatory stringency. The low regulatory stringency countries include those intending to continue to utilize their fossil fuels for hydrogen production, such as Australia, Colombia, Finland, Japan, Paraguay, Poland, Russia, and the UAE. Some of the South American countries, such as Paraguay, intend to use their renewable power potential, but the country does not yet have a certification scheme for export. Given green hydrogen certifications are almost necessary for Paraguay as an export-oriented country, the country is likely to move up the green hydrogen regulatory stringency scale [119]. Finland and Poland do not have explicit hydrogen certifications either, but both countries will likely be impacted by the proposed RED II revision [120] as EU member states. Australia, Colombia, Russia, and the UAE are located in this group mainly because of the lack of fossil-fuel penalties as compared with countries in the low regulatory stringency group. These countries also tend to have a "balanced" approach for fossil fuel and renewable hydrogen [46]. For instance, although the UAE has established the world's largest green hydrogen infrastructure so far; blue hydrogen associated with CCS is still the mid- to long-term strategy given its abundant natural gas resources [121].

The medium regulatory stringency group includes Canada, the Czech Republic, the EU, France, Germany, Hungary, Morocco, the Netherlands, the Republic of Korea, Slovakia, Ukraine, and the UK. The EU and most EU members are in this group. These are all industrialized nations with solid infrastructure, and most of the countries include decarbonization in their national hydrogen strategies. Countries are located in this group because of their explicit or de facto support for technology neutrality as their principle. What is reflected by this principle is a more incremental transitional pathway as compared with the high regulatory stringency group. The EU has been clear about its deployment of hydrogen in the short term (balanced development of both blue and green hydrogen) and long-term priority of renewable hydrogen.

The high regulatory stringency group includes Chile, Italy, New Zealand, and Spain. These countries have all the regulatory measures in place. Italy, Portugal, and Spain are the EU member states that are exclusively supporting green hydrogen in their national strategies. New Zealand is positioning hydrogen as a premium sustainable good and focusing on establishing standards for export [34], and it has been clear that the government is not supporting CCS technologies. Chilean government studies indicate that Chile will have the lowest green hydrogen production cost in the world. The Chilean government ambitiously targets exporting its energy to the rest of the world before the end of the decade and estimates that, by 2050, revenues from exports of green hydrogen could comprise up to 10% of the Chilean GDP [20].

Portugal is the only country in the "green-hydrogen-now" group because it has all three regulatory measures in place, and it has already phased out coal at the time of writing [89]. Portugal is a renewable resource-rich country aiming to become a leading exporter of green hydrogen. The Portugal hydrogen strategy envisages over 2.85 billion EUR for investment and construction of a large-scale solar power plant for hydrogen production to cover domestic and European demand. Portugal is the only country that meets the temporal dimension as compared with countries in the high regulatory stringency group.

4.2. Further Regulatory Challenges

The purpose of this article is not to present a scoreboard of the national hydrogen strategies. First, national hydrogen strategies are a fast-evolving space, and some of the results may become obsolete soon after the article is published. Second, scoring and ranking may become reductionist objectives themselves, which may divert attention from challenges confronting a stringent hydrogen regulation that is genuinely contributing to rapid decarbonization. This section discusses some of the regulatory challenges revealed in this study.

4.2.1. Lost Environmental Rigor in Characterizing "Green", "Clean", and "Low-Carbon" Hydrogen

In addition to the color-band terminologies, we also observe that terms such as clean hydrogen, low-carbon hydrogen, and zero-emission hydrogen appear in some national strategies. The environmental rigor that should otherwise be manifested by these terms is lost. For instance, Australia's National Hydrogen Strategy carefully avoids using the term "green hydrogen", other than referring to existing projects. Blue hydrogen does not appear in the report at all. Instead, it recognizes that "Australia has the resources, and the experience, to take advantage of increasing global momentum for clean hydrogen and make it our next energy export" [18] (p. viii). Clean hydrogen is defined as being "produced using renewable energy or using fossil fuels with substantial carbon capture and storage (CCS). This definition reflects a technology-neutral stance" [18] (p. xiv). This definition reveals the common problems of using terms such as green or clean (while appealing to consumers, they disassociate the terms from technicalities about their climate impact), their production pathways, the estimated emissions intensity, basis of carbon accounting system boundaries and scope, and the consideration of offsets. Many countries also use the term "low-carbon hydrogen" in their national hydrogen strategy. While this term seems to be more closely associated with the decarbonization objective, the sole focus on carbon emissions may ignore other potential environmental and social risks arising from the hydrogen production process (in particular from nuclear power).

The literature has warned that the "lack of consensus and clear definition in the realm of environmental marketing allows many marketers to slip through the reasonable consumer inquiry despite falsely suggesting or implying an environmental benefit" [118] (p. 253), and it calls for clarification and bright-line "green" definitions by the government to prevent greenwashing. However, our findings in the hydrogen strategies reveal that even government definitions may not guarantee the rigor of the concept of "green" to achieve environmental objectives. In some countries, such as the Netherlands, reliable hydrogen development pathways are still debated [122]. In countries such as Canada, the Czech Republic, Hungary, India, Japan, Poland, Russia, Slovakia, the UAE, Ukraine, and the US that have existing nuclear power generation capacity, producing hydrogen from nuclear power is often presented as an opportunity to continue using their nuclear power. Declaring green characteristics in national hydrogen strategies not only increases their acceptance, but the regulatory power to define and characterize "green", "low-carbon", or "clean" hydrogen in national hydrogen strategies also brings an opportunity to adjust the shades of "green" in the context of energy trilemma.

An implicit context for the green characterization in national hydrogen strategies is the knowledge and industrial foundations that have already been set in a specific country. Most of the value associated with hydrogen investments is expected to be created in knowledge-intensive sectors, such as chemicals, mechanical engineering, and electrical equipment. Countries with industrial infrastructure in place may benefit from the deployment of low-carbon hydrogen technologies. No country characterizes the characteristics of green hydrogen without referring to its existing industrial strength, natural resource endowments and demands, or its entire energy mix in the decades to come.

As pointed out by Gunningham [123], the three objectives of affordability, reliability, and sustainability in energy governance may not be met at the same time. Among the three dimensions, the major tradeoff for hydrogen deployment is between cost and climate commitment [124]. In the context of the energy trilemma, green hydrogen, low-carbon hydrogen, and clean hydrogen definitions and characterizations often lose environmental rigor because they are characterized by the combination of genuine intentions to achieve decarbonization and other more strategic considerations. Even if the discourse on hydrogen categorization is changed from color-band terms to more science-based terms [125] (p. 8), the lack of environmental rigor may persist, as long as these underpinning calculations beyond sustainability remain.

4.2.2. Inarticulate Objectives for Applying Technology Neutrality

Technology neutrality seems to be the principle to blur the boundary of innovation support between renewable energy-based hydrogen and fossil-fuel-based hydrogen. Except for countries like Chile, Italy, New Zealand, Portugal, and Spain that are solely focusing on developing and supporting renewable hydrogen, many countries rely on technology neutrality to continue their support for fossil-fuel hydrogen. For instance, in the EU's hydrogen strategy, renewable hydrogen is referred to as the priority for the EU because it is the most compatible with the EU's climate neutrality and zero pollution goals in the long term and most coherent with an integrated energy system [23] (p. 5). Nevertheless, other forms of low-carbon hydrogen are needed in the short and medium term, primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen [23] (p. 5). However, while this principle can be interpreted as technologies that are functional equivalent to achieve an objective should be equally treated, objectives in the national hydrogen strategies are often multifaceted and not clearly articulated for this principle. The Czech Republic interprets this principle by taking low emissions intensity as the objective and states technology neutrality as the reason "why this strategy does not prescribe any target quantities for individual low-carbon hydrogen production technologies as part of the forecast" [22] (p. 42). Hydrogen produced from nuclear power is characterized as low-carbon hydrogen because hydrogen with a minimal carbon footprint can be produced by using electricity generated from nuclear sources to electrolyze water or using high temperatures to directly decompose water [22] (p. 16). Even this principle is not articulated, the US hydrogen strategy simply states that hydrogen is versatile; it can be produced from renewables, nuclear, natural gas, coal, and oil. There was no particular emphasis on which production pathways should be prioritized. Therefore, when adopting the principle, countries need to be clear about environmental and social objectives that the functions of technologies are to be benchmarked. Otherwise, this principle can easily be interpreted in a way that as long as technologies can produce goods with the same use value, they need to be equally supported, which will undermine the expected climate and social benefits of hydrogen.

4.2.3. Trading Hydrogen in a Global Market

Hydrogen will become a globally traded good because the domestic use of hydrogen is limited to hard-to-abate industries like steelmaking and long-distance transport. However, the current national hydrogen strategies have increased regulatory fragmentation, which may not benefit international trade in renewable hydrogen. Our analysis has identified the following challenges:

- Varied fossil-fuel penalties temporally and geographically

While positioning countries as importing and exporting countries of hydrogen [54] is beyond the scope of regulatory stringency, we do find that varied fossil-fuel penalties both temporally and geographically may discourage regulatory stringency in exporting countries. While importing countries could consider climate objectives and require imports of certified green or low-carbon hydrogen instead of fossil-fuel-based hydrogen, the varied fossil-fuel phasing-out timelines mean that, until the latest decarbonization timeline approaches, there is always a market in the world demanding fossil-fuel hydrogen. At any given time, there is always an importing country willing to accept fossil-fuel hydrogen as long as it is cheaper. As early as 2018, Japan, as a major hydrogen importer, dispatched diplomats and industrial stakeholders to engage with Australia, Brunei, Norway, and Saudi Arabia on hydrogen fuel procurement with price as the primary concern [53]. Compared with importing countries that target certified green/renewable hydrogen, the Japanese market is open for fossil-fuel hydrogen now and in the foreseeable future.

- Tradeoffs between costs and comparability in certifications

Certifications are a preferable regulatory measure to define and differentiate hydrogen types partly because of their voluntary noninterventionist nature. In each certification, there is a tradeoff between the level of rigor and credibility versus the burden placed upon market players using the certification and the number of participants [109]. For instance, the EU's CertifHy is the world's most mature certification scheme, and it has the ambition to expand users by interoperating with or recognizing some domestic certifications of its member states. However, the Czech Republic defines hydrogen produced from nuclear power as "low-carbon" hydrogen. If CertifHy recognizes Czech's nuclear-based hydrogen as directly part of its low-carbon hydrogen, it means a sacrifice of environmental rigor, which will impede its credibility. Without direct recognition or interoperating arrangement, Czech hydrogen producers can only apply for double certification with extra cost or be excluded from the CertifHy system. The rigor of certifications is directly related to the categorization issue discussed in Section 4.2.1. Moreover, availability of more than one certification in a jurisdiction provides the opportunity for producers to choose to comply with the less stringent regulation and still get labeling of green or low-carbon hydrogen. In addition to the potential problem of racing to the bottom, at least in the short term [81], private industry-led certifications may not be obligated to provide their technical standards to the general public. For instance, the Australian Smart Energy Council, despite claiming its certifications are for zero-carbon hydrogen, does not make clear whether it needs to be produced from 100% renewable hydrogen resources. The lack of this information makes it impossible to compare the stringency of certifications. On the other hand, more information required by a certification scheme means higher reporting efforts and may incur higher costs for producers. Globally, the market for certifications [67] makes it difficult to compare different terms in different systems internationally. This has been identified as a potential barrier to green hydrogen trade internationally [69].

International organizations such as IRENA have already been involved in countries' development of certifications to prevent the proliferation of incompatible certifications. For instance, it established a Collaborative Framework on Green Hydrogen so that green hydrogen exporters such as Morocco can participate and understand the demand of the EU and engage with the EU on a pilot of CertifHy. Bilaterally, Germany has actively engaged with potential exporting countries such as Chile and the UAE to enhance their regulatory capacity, including establishing a certification scheme.

While renewable hydrogen is clearly a type of environmental good which produces less GHG emissions than its traditional counterparts, the current international trade law requires that green hydrogen should not be treated preferably compared to fossil-fuel hydrogen according to the principles of nondiscrimination. Should such preferable treatment occur, relevant regulations may be subject to the dispute settlement in the World Trade Organization (WTO). For instance, if one country establishes internal regulation to only import certain certified green or low-carbon hydrogen, such regulation may be considered as discrimination against hydrogen produced through other pathways and be sued at the WTO. These challenges of trading hydrogen in a globalized market need to be addressed to have a sustainable hydrogen economy.

4.3. Limitations of the Study

The typology approach with binary criteria involves some limitations. First, the scope of countries we examined involved those with national (regional) level hydrogen strategies in place. This does not include hydrogen inspirations at subnational levels or the hydrogen economy as a whole. There are countries where national strategies are absent, but local level strategies exist, e.g., China. Despite China having issued city-based rewards and subsidies [126], and currently being the largest gray hydrogen producer in the world, we did not include it in our analysis because the country as a whole does not meet our selection criteria.

The second issue relates to the parameters. Despite our efforts to describe various combinations of issues and policies around green hydrogen, our typology is built on the literature with a pre-existing limitation—using decarbonization objective as a proxy for greenness (in our research question) of hydrogen. In the framework, sustainability parameters other than carbon emissions are not included, such as biodiversity [127] and water consumption for electrolyzation [128]. Likewise, other important issues such as indigenous land rights and other socioeconomic impacts are not considered in this study. Given this understanding of green hydrogen as hydrogen with zero or low-carbon emissions being not only predominant in the literature but also the national hydrogen strategies per se, other sustainability dimensions are rarely mentioned in national hydrogen strategies as measurable parameters.

Thirdly, we have to balance the breadth and depth of information in the analysis. While acknowledging that detailed technical parameters such as thresholds of emission intensities [10] (p. 2) are important, we refer to the broader regulatory measures in national hydrogen strategies and primary implementing regulations to reveal a panorama of decarbonization commitments and efforts in national hydrogen strategies. The parameters we use are incommensurable; thus, we take a typology approach instead of quantitative analysis of providing a weight for a certain parameter. Our result does reveal the level of regulatory stringency of green hydrogen in national hydrogen strategies as groups, but not as rankings. This is a precautious decision before the perception of the relative importance of the parameters is clear. The Spanish hydrogen strategy maintains that carbon taxes can help provide the right signals for stakeholders and consumers to correctly assess renewable labeling. While the interrelation between parameters like this is an important issue, we did not cover it in this study.

5. Conclusions

This paper took a typology approach and set up a framework to measure regulatory stringency for green hydrogen in national hydrogen strategies with four parameters: temporal parameter, fossil-fuel penalties, hydrogen certifications, and innovation enablement. The temporal parameter of green hydrogen uptake rates countries' hydrogen strategies according to their readiness for green hydrogen, namely, zero stringency, scale first and clean later, and green hydrogen now. Then, it follows three secondary-level parameters that further distinguish the countries in the scale first and clean later group. Firstly, given that information of fossil fuel hydrogen phasing-out timelines is rarely included in national hydrogen strategies, we use proxy indicators of fossil-fuel penalties which include coal phasing-out timelines and carbon pricing to measure efforts to quit fossil fuels. Secondly, we consider hydrogen certification schemes that are used to differentiate renewable, low-carbon, clean, or blue hydrogen. Thirdly, we take into account innovation enablement as the last secondary-level parameter that identifies a country's future innovation support—whether it is exclusively dedicated to renewable hydrogen. Technology neutrality is a critical indicator of equal innovation support for fossil-fuel hydrogen-related technologies such as CCS and renewable hydrogen technologies. When technology neutrality is not specifically mentioned, we use contextual information to verify whether only renewable hydrogen innovation is supported by public funds. Fossil-fuel penalties discourage hydrogen produces from fossil-fuel sources of hydrogen, certifications differentiate hydrogen based on their embedded carbon emissions, and green hydrogen enablement provides dedicated support for renewable hydrogen technologies. Altogether, these measures guarantee that renewable hydrogen is differentiated and supported in financing, production, and trade beyond market prices. The temporal dimension further emphasizes the timeframe of the commitment to quit fossil fuels.

Using the typology, we identified a spectrum of green hydrogen regulatory stringency in the national hydrogen strategies. Most countries are located in the transitioning group—scale first and clean later. According to the criteria of this category, this finding implies that most countries with national hydrogen strategies are prioritizing the scaling up of the hydrogen economy to meet their domestic or export demands. Climate objectives are part of the agenda, but their stringency is not guaranteed because of the lack of comprehensive and prescriptive regulatory measures.

We further classified the major scale first and clean later group into three levels, i.e., low regulatory stringency, medium regulatory stringency, and high regulatory stringency, depending on the number of parameters that a national hydrogen strategy satisfies. The low regulatory stringency group includes countries envisaging deploying fossil fuels and nuclear power and engaging in incremental transition. The medium regulatory stringency level includes most industrialized countries that rely on the principle of technology neutrality to support CCS technologies in the short term. Without such regulations, primarily price-based competition may not recognize the value of green hydrogen. The high regulatory stringency group comprises those close to reaching their coal phase-out timeline, with all the regulations in place. Portugal is the only country located in the green hydrogen now group, because it has all three secondary parameters satisfied in its national hydrogen strategy, and it has already phased out coal.

In addition to the result, we further discussed challenges to achieve stringent green hydrogen regulation, including the lost environmental rigor in characterizing and categorizing green hydrogen, an inarticulate objective for technology neutrality, and regulatory challenges for trading hydrogen in a global market.

Author Contributions: Conceptualization, W.C. and S.L.; methodology, W.C. and S.L.; investigation, W.C. and S.L.; writing—original draft preparation, W.C. and S.L.; writing—review and editing, W.C.; visualization, S.L.; supervision, W.C.; funding acquisition, W.C. All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful for funding under the Australian National University's Zero-Carbon Energy for the Asia-Pacific Grand Challenge and the Australian National University College of Law's 2020 New Research Individual Grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: We acknowledge that transdisciplinary discussions at the fortnightly Hydrogen Fuels Project meetings at the Zero-Carbon Energy for the Asia-Pacific Grand Challenge provided useful information for this article. We thank Thomas Longden and coauthors for their authorization to reproduce Figure 2 from their publication.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. van Renssen, S. The hydrogen solution? *Nat. Clim. Change* **2020**, *10*, 799–801. [CrossRef]
2. International Renewable Energy Agency (IRENA). Hydrogen: A Renewable Energy Perspective. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf (accessed on 26 December 2021).
3. IRENA. Green Hydrogen: A Guide to Policy Making. 2020. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf (accessed on 26 December 2021).
4. Hanley, E.S.; Deane, J.P.; Gallachóir, B.P.Ó. The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3027–3045. [CrossRef]
5. Chapman, A.; Itaoka, K.; Hirose, K.; Davidson, F.T.; Nagasawa, K.; Lloyd, A.C.; Webber, M.E.; Kurban, Z.; Managi, S.; Tamaki, T.; et al. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. *Int. J. Hydrog. Energy* **2019**, *44*, 6371–6382. [CrossRef]
6. Staffell, I.; Scamman, D.; Velazquez Abad, A.; Balcombe, P.; Dodds, P.E.; Ekins, P.; Shah, N.; Ward, K.R. The role of hydrogen and fuel cells in the global energy system. *Energy Environ. Sci.* **2019**, *12*, 463–491. [CrossRef]
7. Noussan, M.; Raimondi, P.P.; Scita, R.; Hafner, M. The role of green and blue hydrogen in the energy transition—a technological and geopolitical perspective. *Sustainability* **2021**, *13*, 298. [CrossRef]
8. Aisbett, E.; Cheng, W.; Beck, F. Green Industrial Policy and Technology Neutrality: Odd Couple or Unholy Marriage? ZCEAP Working Paper 01-21. Australian National University. 2021. Available online: https://www.anu.edu.au/files/document-collection/ZCWP01-21%20Green%20Industrial%20Policy%20and%20Technology%20Neutrality_2.pdf (accessed on 26 December 2021).
9. Velazquez Abad, A.; Dodds, P.E. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy* **2020**, *138*, 111300. [CrossRef]
10. Longden, T.; Beck, F.J.; Jotzo, F.; Andrews, R.; Prasad, M. 'Clean' hydrogen?—Comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen. *Appl. Energy* **2022**, *306*, 118145. [CrossRef]
11. World Energy Council. National Hydrogen Strategies. 2021. Available online: https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf (accessed on 26 December 2021).
12. Damman, S.; Sandberg, E.; Rosenberg, E.; Pisciella, P.; Graabak, I. A hybrid perspective on energy transition pathways: Is hydrogen the key for Norway? *Energy Res. Soc. Sci.* **2021**, *78*, 102116. [CrossRef]
13. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
14. Andrews, J.; Shabani, B. The role of hydrogen in a global sustainable energy strategy. *Wiley Interdiscip. Rev. Energy Environ.* **2014**, *3*, 474–489. [CrossRef]
15. Chaube, A.; Chapman, A.; Shigetomi, Y.; Huff, K.; Stubbins, J. The role of hydrogen in achieving long term Japanese energy system goals. *Energies* **2020**, *13*, 4539. [CrossRef]
16. Albrecht, U.; Bünger, U.; Michalski, J.; Raksha, T.; Wurster, R.; Zerhusen, J. International Hydrogen Strategies—A study commissioned by and in cooperation with the World Energy Council Germany. In *Ludwig-Bölkow-Syst. GmbH Weltenergierat-Dtschl*; World Energy Council Germany: Ottobrunn, Germany, 2020.
17. CSIRO HyResource International. Available online: https://research.csiro.au/hyresource/policy/international/ (accessed on 15 November 2021).
18. COAG Australia. *Australia's National Hydrogen Strategy*; COAG Australia: Canberra, Australia, 2019. Available online: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf (accessed on 26 December 2021).
19. Natural Resources Canada. Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen: A Call to Action. 2020. Available online: https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen%20Strategy%20for%20Canada%20Dec%2015%202200%20clean_low_accessible.pdf (accessed on 26 December 2021).
20. Ministry of Energy Government of Chile. National Green Hydrogen Strategy: Chile, a Clean Energy Provider for a Carbon Neutral Planet. 2020. Available online: https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf (accessed on 26 December 2021).
21. Minenergía Colombia. Colombia's Hydrogen Roadmap. 2021. Available online: https://www.minenergia.gov.co/documents/10192/24309272/Colombian+Hydrogen+Roadmap.pdf (accessed on 26 December 2021).

22. Ministry of Industry and Trade the Czech Republic. The Czech Republic's Hydrogen Strategy. 2021. Available online: https://www.mpo.cz/assets/cz/prumysl/strategicke-projekty/2021/9/Hydrogen-Strategy_CZ_2021-09-09.pdf (accessed on 26 December 2021).
23. European Commission. *A hydrogen strategy for a climate-neutral Europe: Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. 2020, COM(2020) 301 final. Available online: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (accessed on 26 December 2021).
24. Laurikko, J.; Ihonen, J.; Kiviaho, J.; Himanen, O.; Weiss, R.; Saarinen, V.; Kärki, J.; Hurskainen, M. National Hydrogen Roadmap for Finland. 2020. Available online: https://www.businessfinland.fi/4abb35/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/alykas-energia/bf_national_hydrogen_roadmap_2020.pdf (accessed on 26 December 2021).
25. France Hydrogène. Trajectoire Pour une Grande Ambition Hydrogène. 2021. Available online: https://s3.production.france-hydrogene.org/uploads/sites/4/2021/11/France_20Hydrog_C3_A8ne_trajectoire_20grande_20ambition_20H2_final_web.pdf (accessed on 26 December 2021).
26. Federal Ministry for Economic Affairs and Energy of Germany. The National Hydrogen Strategy. 2020. Available online: https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6 (accessed on 26 December 2021).
27. Government of Hungary. Hungary's National Hydrogen Strategy. 2021. Available online: https://cdn.kormany.hu/uploads/document/a/a2/a2b/a2b2b7ed5179b17694659b8f050ba9648e75a0bf.pdf (accessed on 26 December 2021).
28. Priya, L. India's National Hydrogen Mission and Prospects for Cooperation with GCC. 2021. Available online: https://idsa.in/issuebrief/india-national-hydrogen-mission-n-gcc-lpriya-270821 (accessed on 26 December 2021).
29. Manna, J.; Jha, P.; Sarkhel, R.; Banerjee, C.; Tripathi, A.K.; Nouni, M.R. Opportunities for green hydrogen production in petroleum refining and ammonia synthesis industries in India. *Int. J. Hydrog. Energy* **2021**, *46*, 38212–38231. [CrossRef]
30. Ministry of Economic Development Italy. Strategia Nazionale Idrogeno Linee Guida Preliminari (National Hydrogen Strategy Preliminary Guidelines). 2020. Available online: https://www.mise.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf (accessed on 26 December 2021).
31. Ministerial Council on Renewable Energy, Hydrogen and Related Issues Japan. Basic Hydrogen Strategy of Japan. 2017. Available online: https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf (accessed on 26 December 2021).
32. CSIRO. Morocco -HyResource. Available online: https://research.csiro.au/hyresource/policy/international/morocco/ (accessed on 26 December 2021).
33. Rijksoverheid the Netherlands. Netherlands Government Strategy on Hydrogen. 2020. Available online: https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen (accessed on 26 December 2021).
34. Ministry of Business, Innovation & Employment New Zealand. A Vision for Hydrogen in New Zealand: Green Paper. 2019. Available online: https://www.mbie.govt.nz/dmsdocument/6798-a-vision-for-hydrogen-in-new-zealand-green-paper (accessed on 26 December 2021).
35. Norwegian Ministry of Petroleum and Energy; Norwegian Ministry of Climate and Environment. The Norwegian Government's Hydrogen Strategy: Towards a Low Emission Society. 2020. Available online: https://www.regjeringen.no/contentassets/40026db2148e41eda8e3792d259efb6b/y-0127e.pdf (accessed on 26 December 2021).
36. Paraguay Government. Towards the Green Hydrogen Route in Paraguay—Conceptual Framework. 2021. Available online: https://www.ssme.gov.py/vmme/pdf/H2/DIGITAL_ENG_H2_Marco_Conceptual.pdf (accessed on 26 December 2021).
37. Government of Poland. Polish Hydrogen Strategy until 2030 with an Outlook until 2040. 2021. Available online: https://bip.mos.gov.pl/fileadmin/user_upload/bip/dostep_do_informacji/Projekt_PSW.pdf (accessed on 26 December 2021).
38. Presidency of the Council of Ministers Portugal. Council of Ministers Resolution n.º 63/2020—National Plan for Hydrogen Portugal. 2020. Available online: https://dre.pt/dre/detalhe/resolucao-conselho-ministros/63-2020-140346286 (accessed on 26 December 2021).
39. de Sousa, A.L.; Cascão, V. A Simplified Guide to the Portuguese Hydrogen Strategy. Available online: https://www.vda.pt/xms/files/05_Publicacoes/2020/Flashes_Newsletters/VdA_-_Guide_to_the_Portuguese_Hydrogen_Strategy.pdf (accessed on 25 December 2021).
40. Government of Korea. Hydrogen Economy: Roadmap of Korea. 2019. Available online: http://www.motie.go.kr (accessed on 26 December 2021).
41. Josefson, J.; Rotar, A. Russia Releases Hydrogen Roadmap. Available online: https://www.morganlewis.com/pubs/2020/11/russia-releases-hydrogen-roadmap (accessed on 25 December 2021).
42. Barlow, I.; Tsafos, N. Russia's Hydrogen Energy Strategy. Available online: https://www.csis.org/analysis/russias-hydrogen-energy-strategy (accessed on 25 December 2021).
43. Sinay, J.; Jesný, M.; Weiterschütz, J.; Blaškovitš, P.; Sulík, R. Národná vodíková stratégia: Pripravení na budúcnosť (National Hydrogen Strategy of the Slovak "Ready for the Future"). 2021. Available online: https://rokovania.gov.sk/download.dat?id=361F8BABC3FC4DED81622AEAC353040C-7E6A87522DA19835FF227E896470F449 (accessed on 26 December 2021).
44. Ministry for the Ecological Transition and the Demographic Challenge (MITERD) of Spain. Hoja de Ruta del Hidrógeno: Una Apuesta por el Hidrógeno Renovable (Hydrogen Roadmap: A Commitment to Renewable Hydrogen). 2020. Available online: https://energia.gob.es/es-es/Novedades/Documents/hoja_de_ruta_del_hidrogeno.pdf (accessed on 26 December 2021).

45. UNECE Ukraine. Draft Roadmap for Production and Use of Hydrogen in Ukraine. 2020. Available online: https://unece.org/sites/default/files/202103/Draft%20Roadmap%20for%20production%20and%20use%20of%20hydrogen%20in%20Ukraine_Final%20.pdf (accessed on 26 December 2021).
46. Friedmann, J.; Mills, R. The UAE's Role in the Global Hydrogen Economy. 2021. Available online: https://www.qamarenergy.com/sites/default/files/The%20UAE%27s%20Role%20in%20the%20Global%20Hydrogen%20Economy.pdf (accessed on 26 December 2021).
47. Ibrahim, L.; Hussein, H. UAE Announces Hydrogen Leadership Roadmap, Reinforcing Nation's Commitment to Driving Economic Opportunity through Decisive Climate Action. Available online: https://www.wam.ae/en/details/1395302988986 (accessed on 26 December 2021).
48. The Secretary of State for Business, Energy & Industrial Strategy UK. UK Hydrogen Strategy. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf (accessed on 26 December 2021).
49. Department of Energy US. Hydrogen Strategy: Enabling A Low-Carbon Economy. 2020. Available online: https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf (accessed on 26 December 2021).
50. Gawlik, L.; Mokrzycki, E. Analysis of the polish hydrogen strategy in the context of the EU's strategic documents on hydrogen. *Energies* **2021**, *14*, 6382. [CrossRef]
51. Ren, X.; Dong, L.; Xu, D.; Hu, B. Challenges towards hydrogen economy in China. *Int. J. Hydrog. Energy* **2020**, *45*, 34326–34345. [CrossRef]
52. Stangarone, T. South Korean efforts to transition to a hydrogen economy. *Clean Technol. Environ. Policy* **2021**, *23*, 509–516. [CrossRef] [PubMed]
53. Nagashima, M. Japan's Hydrogen Strategy and Its Economic and Geopolitical Implications. 2018. Available online: https://www.ifri.org/sites/default/files/atoms/files/nagashima_japan_hydrogen_2018_.pdf (accessed on 26 December 2021).
54. Van de Graaf, T.; Overland, I.; Scholten, D.; Westphal, K. The new oil? The geopolitics and international governance of hydrogen. *Energy Res. Soc. Sci.* **2020**, *70*, 101667. [CrossRef]
55. Koneczna, R.; Cader, J. Hydrogen in the strategies of the european Union member states. *Gospod. Surowcami Miner./Miner. Resour. Manag.* **2021**, *37*, 53–74. [CrossRef]
56. Bhagwat, S.R.; Olczak, M. Green Hydrogen Bridging the Energy Transition in Africa and Europe. 2020. Available online: https://africa-eu-energy-partnership.org/wp-content/uploads/2021/04/AEEP_Green-Hydrogen_Bridging-the-Energy-Transition-in-Africa-and-Europe_Final_For-Publication_2.pdf (accessed on 26 December 2021).
57. Pudukudy, M.; Yaakob, Z.; Mohammad, M.; Narayanan, B.; Sopian, K. Renewable hydrogen economy in Asia—Opportunities and challenges: An overview. *Renew. Sustain. Energy Rev.* **2014**, *30*, 743–757. [CrossRef]
58. Cashore, B.; Knudsen, J.S.; Moon, J.; van der Ven, H. Private authority and public policy interactions in global context: Governance spheres for problem solving. *Regul. Gov.* **2021**, *15*, 1166–1182. [CrossRef]
59. IRENA. Hydrogen from Renewable Power: Technology Outlook for the Energy Transition. 2018. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf (accessed on 26 December 2021).
60. IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. 2021. Available online: https://www.iea.org/reports/net-zero-by-2050 (accessed on 26 December 2021).
61. Garza, A.D. La Fossil Fuel Companies Say Hydrogen Made From Natural Gas Is a Climate Solution. But the Tech May Not Be Very Green. Available online: https://time.com/6098910/blue-hydrogen-emissions/ (accessed on 13 December 2021).
62. Glasgow Breakthroughs. Available online: https://racetozero.unfccc.int/system/glasgow-breakthroughs/ (accessed on 23 November 2021).
63. Saeedmanesh, A.; Mac Kinnon, M.A.; Brouwer, J. Hydrogen is essential for sustainability. *Curr. Opin. Electrochem.* **2018**, *12*, 166–181. [CrossRef]
64. Szabo, J. Fossil Capitalism's Lock-ins: The Natural Gas-Hydrogen Nexus. *Capital. Nat. Social.* **2020**, *32*, 91–110. [CrossRef]
65. IEA. World Energy Outlook 2021—Revised Version October 2021. 2021. Available online: https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf (accessed on 26 December 2021).
66. World Bank. What Is Carbon Pricing? Carbon Pricing Dashboard. Available online: https://carbonpricingdashboard.worldbank.org/what-carbon-pricing (accessed on 13 December 2021).
67. Mol, A.P.J.; Oosterveer, P. Certification of markets, markets of certificates: Tracing sustainability in global agro-food value chains. *Sustainability* **2015**, *7*, 12258–12278. [CrossRef]
68. Piebalgs, A.; Jones, C. A Proposal for a Regulatory Framework for Hydrogen Guarantees of Origin. *FSR Policy Brief* **2020**. Available online: https://cadmus.eui.eu/bitstream/handle/1814/68779/PB_2020_37_FSR.pdf?sequence=1 (accessed on 13 December 2021).
69. White, L.V.; Fazeli, R.; Cheng, W.; Aisbett, E.; Beck, F.J.; Baldwin, K.G.H.; Howarth, P.; O'Neill, L. Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting. *Energy* **2020**, *215*, 119139. [CrossRef]
70. DISER. A Hydrogen Guarantee of Origin Scheme for Australia—Discussion Paper. 2021. Available online: https://storage.googleapis.com/converlensauindustry/industry/p/prj1a3de348a6c0ad7d282f7/public_assets/Discussion%

20paper%20-%20A%20Hydrogen%20Guarantee%20of%20Origin%20Scheme%20for%20Australia.pdf (accessed on 26 December 2021).
71. Boretti, A. Production of hydrogen for export from wind and solar energy, natural gas, and coal in Australia. *Int. J. Hydrog. Energy* **2020**, *45*, 3899–3904. [CrossRef]
72. Alex, B.; Yafimava, K. *EU Hydrogen Vision: Regulatory Opportunities and Challenges*; The Oxford Institute for Energy Studies: Oxford, UK, 2020; pp. 1–17.
73. Rios, M.D. Technological Neutrality and Conceptual Singularity. *SSRN Electron. J.* **2013**, *2198887*. [CrossRef]
74. Ohm, P. The argument against technology-neutral surveillance laws. *Tex. Law Rev.* **2010**, *88*, 1685–1713.
75. Selvadurai, N. The Relevance of Technology Neutrality to the Design of Laws to Criminalise Cyberbullying. *Int. J. Law Public Adm.* **2018**, *1*, 14. [CrossRef]
76. Wylly, P. Evaluating the Costs of Technology Neutrality in Light of the Importance of Social Network Influences and Bandwagon Effects for Innovation Diffusion. *N. Y. Univ. Law J.* **2015**, *23*, 300–352.
77. Bushnell, J.B.; Muehlegger, E.J.; Rapson, D.S.; Witcover, J. The End of Neutrality? LCFS, Technology Neutrality, and Stimulating the EV Market. 2021. Energy Institute WP 318R. Available online: https://haas.berkeley.edu/wp-content/uploads/WP318.pdf (accessed on 26 December 2021).
78. Netherlands Enterprise Agency. India's Ambition and Potential to Become World's Largest Green Hydrogen Exporter. 2021. Available online: https://www.rvo.nl/sites/default/files/2021/09/India-kansenbericht-hydrogen.pdf (accessed on 26 December 2021).
79. Japan's Ministry of Energy, Trade, and Industry. Green Growth Strategy through Achieving Carbon Neutrality in 2050. 2021. Available online: https://www.meti.go.jp/english/press/2020/pdf/1225_001b.pdf (accessed on 26 December 2021).
80. Earnhart, D.; Rassier, D.G. "Effective regulatory stringency" and firms' profitability: The effects of effluent limits and government monitoring. *J. Regul. Econ.* **2016**, *50*, 111–145. [CrossRef]
81. Judge-Lord, D.; McDermott, C.L.; Cashore, B. Do Private Regulations Ratchet Up? How to Distinguish Types of Regulatory Stringency and Patterns of Change. *Organ. Environ.* **2020**, *33*, 96–125. [CrossRef]
82. Brunel, C.; Levinson, A. *Measuring Environmental Regulatory Stringency*; OECD Working Paper; OECD: Paris, France, 2013. [CrossRef]
83. Koziuk, V.; Hayda, Y.; Dluhopolskyi, O.; Klapkiv, Y. Stringency of environmental regulations vs. Global competitiveness: Empirical analysis. *Econ. Sociol.* **2019**, *12*, 264–284. [CrossRef]
84. Hemphill, T.A. From Industrial Policy to National Industrial Strategy: An Emerging Global Phenomenon. *Bull. Sci. Technol. Soc.* **2020**, *38*, 39–42. [CrossRef]
85. Parra, P.A.Y.; Ganti, G.; Brecha, R.; Hare, B.; Schaeffer, M.; Fuentes, U. Global and Regional Coal Phase-Out Requirements of the Paris Agreement: Insights from the IPCC Special Report on 1.5 °C. Report by Climate Analytics 2019. Available online: https://climateanalytics.org/media/report_coal_phase_out_2019.pdf (accessed on 26 December 2021).
86. Sheldrick, A.; Obayashi, Y. Japan, Once a Leader on Climate, under Fire for Coal Use at COP26. Available online: https://www.reuters.com/business/cop/japan-once-leader-climate-under-fire-coal-use-cop26-2021-11-09/ (accessed on 25 December 2021).
87. Dave JonesToday's New Coal Phase-Out Announcements: An Explainer—Ember Today's New Coal Phase-Out Announcements: An Explainer. Available online: https://ember-climate.org/commentary/2021/11/04/todays-new-coal-phase-out-announcements-an-explainer/ (accessed on 25 December 2021).
88. Reuters Norway to Close Its Last Arctic Coal Mine in 2023. Available online: https://www.investing.com/news/commodities-news/norway-to-close-its-last-arctic-coal-mine-in-2023-2630781 (accessed on 24 December 2021).
89. Johns, A. Portugal Becomes Fourth EU Country to Quit Coal. Available online: https://industryeurope.com/sectors/energy-utilities/portugal-becomes-fourth-EU-country-to-quit-coal/ (accessed on 16 December 2021).
90. Gumbau, A. The Promise of Ukraine's Unprecedented Coal Phase-Out. Available online: https://www.energymonitor.ai/policy/the-promise-of-ukraines-unprecedented-coal-phase-out (accessed on 23 December 2021).
91. Duggal, H. Infographic: What Has Your Country Pledged at COP26? Available online: https://www.aljazeera.com/news/2021/11/14/infographic-what-has-your-country-pledged-at-cop26 (accessed on 13 December 2021).
92. Europe Beyond Coal. Europe's Coal Exit: Overview of National Coal Phase out Commitments. 2021. Available online: https://beyond-coal.eu/wp-content/uploads/2021/11/Briefing-Overview-of-National-Coal-Phase-out-Commitments-24-November-2021-2.pdf (accessed on 26 December 2021).
93. Beyond Coal. Overview: National Coal Phase-Out Announcements in Europe. 2021. Available online: https://beyond-coal.eu/wp-content/uploads/2021/06/Overview-of-national-coal-phase-out-announcements-Europe-Beyond-Coal-30-June-2021.docx.pdf (accessed on 26 December 2021).
94. UN Climate Change Conference (COP26) COP26 Outcomes. Available online: https://ukcop26.org/the-conference/cop26-outcomes/ (accessed on 13 December 2021).
95. World Bank Carbon Pricing Dashboard: Up-to-Date Overview of Carbon Pricing Initiatives. Available online: https://carbonpricingdashboard.worldbank.org/ (accessed on 14 December 2021).
96. Gregor, E.; Victoria, G.A. *EU hydrogen policy: Hydrogen as an energy carrier for a climate-neutral economy*. European Parliamentary Research Service. 2021. Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689336/EPRS_BRI(2021)689336_EN.pdf (accessed on 14 December 2021).

97. Treadwell, K. EU Hydrogen Strategy Opens Arms to Fossil Fuels. 2020. Available online: https://wwf.panda.org/wwf_news/?364637/EU-Hydrogen-Strategy (accessed on 26 December 2021).
98. Certified Energy. Designing a Renewable Gas Certification System for New Zealand. 2021. Available online: https://www.certifiedenergy.co.nz/_files/ugd/971926_072b40d318e547839ca752fce4b6f0cf.pdf (accessed on 26 December 2021).
99. Smart Energy Council. Zero Carbon Certification Scheme. 2020. Available online: https://smartenergy.org.au/articles/breaking-news-smart-energy-council-launches-zero-carbon-certification-scheme/ (accessed on 26 December 2021).
100. EU Science HUB Renewable Energy—Recast to 2030 (RED II). Available online: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii (accessed on 26 December 2021).
101. Jensterle, M.; Narita, J.; Piria, R.; Samadi, S.; Prantner, M.; Siegemund, S.; Kan, S.; Matsumoto, T.; Shibata, Y.; Thesen, J. The Role of Clean Hydrogen in the Future Energy Systems of Japan and Germany. 2019. Available online: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/The_role_of_clean_hydrogen_in_the_future_energy_systems.pdf (accessed on 26 December 2021).
102. TÜV SÜD. TÜV SÜD Standard CMS 70: Erzeugung von Grünem Wasserstoff (GreenHydrogen). 2020. Available online: https://www.tuvsud.com/de-de/-/media/de/industry-service/pdf/broschueren-und-flyer/is/energie/standard-cms-70-greenhydrogen-ts-is-ut.pdf?la=de-de&hash=73E98931F8657D0313E27ED725C6B45D (accessed on 26 December 2021).
103. Crema, L. Priorities for the Development of a Hydrogen Value Chain in Italy. 2021. Available online: https://www.eai.enea.it/component/jdownloads/?task=download.send&id=1211&catid=61&Itemid=101 (accessed on 26 December 2021).
104. Cova, B.; Migliorini, L. Italian Hydrogen Strategy: What Impact on the Power System? 2021. Available online: https://www.cesi.it/views/cesi-studies-italian-hydrogen-strategy-what-impact-on-the-power-system/ (accessed on 26 December 2021).
105. IRENA. IRENA Members Lay Ground for Green Hydrogen Trading. Available online: https://www.irena.org/newsroom/articles/2021/May/IRENA-Members-Lay-Ground-for-Green-Hydrogen-Trading (accessed on 26 December 2021).
106. IRENA. The World Power-to-X Summit 2020 Session 4 IRENA-Collaborative Framework for Green Hydrogen. 2020. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Articles/2020/Oct/Morocco_PtX_IRENA_session-summary.pdf?la=en&hash=2BF20AE0F8272EF0E813A3E0D78A7A742D904075 (accessed on 26 December 2021).
107. CertifHy. CertifHy Phase III will Implement a Harmonized H2 Guarantee of Origin Scheme. Available online: https://www.tuvsud.com/en/press-and-media/2020/december/certifhy-phase-iii-will-implement-a-harmonized-h2-guarantee-of-origin-scheme (accessed on 25 December 2021).
108. Department of Energy Policy and Regulatory Framework, UAE. Green Hydrogen Middle East. 2021. Available online: https://reglobal.co/wp-content/uploads/2021/09/Carlos-Travesedo_DoE-green-hydrogen-ME-aug21-1.pdf (accessed on 26 December 2021).
109. Schröder, J.; Jörling, K.; Reshma Carmel Francy, F.A.F.; von Zitzewitz, E.; Zangerl, K. The Role of Hydrogen for the Energy Transition in the UAE and Germany A Joint Study by the Emirati-German Energy Partnership. 2021. Available online: https://guidehouse.com/-/media/www/site/downloads/energy/2020/ghhydrogenforenergytransitionintheuaeandde.pdf (accessed on 26 December 2021).
110. UK Department for Business, Energy and Industrial Strategy. Consultation on a UK Low Carbon Hydrogen Standard. 2021. Available online: https://www.gov.uk/government/publications/options-for-a-low-carbon-hydrogen-standard-report (accessed on 26 December 2021).
111. Peacock, B. Australia Wants to Certify Green Hydrogen with German Expertise; PV Magazine International: 2021. Available online: https://www.pv-magazine.com/2021/01/13/australia-wants-to-certify-green-hydrogen-with-german-expertise/ (accessed on 26 December 2021).
112. HINICIO; LBST. Recommendations for a Green Hydrogen Certification Scheme in Chile that is Compatible with National and International Carbon Markets: Advisory Report on the Development of a Green Hydrogen Certification Scheme in Chile. 2021. Available online: https://www.hinicio.com/file/2021/07/Hinicio_green_hydrogen_certification_report_Chile_WB.pdf (accessed on 26 December 2021).
113. Ultimahora. Paraguay Aims to Become "the Largest Hydrogen Producer" in the World. 2021. Available online: https://www-ultimahora-com.translate.goog/paraguay-apunta-convertirse-en-el-mayor-productor-hidrogeno-del-mundo-n2970465.html?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en-GB (accessed on 6 December 2021).
114. Fredriksson, P.G.; Millimet, D.L. Is there a "California effect" in US environmental policymaking? *Reg. Sci. Urban Econ.* **2002**, *32*, 737–764. [CrossRef]
115. Ramesh, M. Bringing Back Reactors for Green Hydrogen. Available online: https://www.thehindubusinessline.com/specials/clean-tech/bringing-back-reactors-for-green-hydrogen/article37938567.ece (accessed on 16 December 2021).
116. Joschka Jahn; Oldag Caspar; Rainer Quitzow; Sonja Thielges; Andrea Wiesholzer Hydrogen: A Future Cornerstone of EU-Russia Energy Relations? Available online: https://www.iass-potsdam.de/en/blog/2021/01/hydrogen-future-cornerstone-eu-russia-energy-relations (accessed on 25 December 2021).
117. Michaelowa, A.; Butzengeiger, S. Breakthrough of Hydrogen Technologies until 2030: Chances and Risks for Gulf Countries, International Policy Implications. 2019. Available online: https://www.zora.uzh.ch/id/eprint/175363/1/ZORA17363.pdf (accessed on 26 December 2021).
118. Feinstein, N. Learning from Past Mistakes: Future Regulation to Prevent Greenwashing. *Boston Coll. Environ. Aff. Law Rev.* **2013**, *40*, 229–258. [CrossRef]

119. New Energy. Q&A with Paraguay's Renewable Energy Chief on the Green Hydrogen Market. Available online: https://newenergyevents.com/qa-with-paraguays-renewable-energy-chief-on-green-hydrogen-market/ (accessed on 16 December 2021).
120. European Commission. *Proposal for a Directive of the European Parliament and of the Council Amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and the Council and Directive 98/70/EC*; European Commission: Brussels, Belgium, 2021.
121. WFW. Hydrogen in the UAE. 2021. Available online: https://www.wfw.com/articles/hydrogen-in-the-uae/ (accessed on 15 December 2021).
122. Schroot, B. The Netherlands: A Blue Hydrogen Economy Now Will Ease a Transition to Green. Available online: https://energypost.eu/the-netherlands-a-blue-hydrogen-economy-now-will-ease-a-transition-to-green/ (accessed on 3 December 2021).
123. Gunningham, N. Managing the energy trilemma: The case of Indonesia. *Energy Policy* **2013**, *54*, 184–193. [CrossRef]
124. Patonia, A. Hydrogen at the Gates: Towards a New Chapter in the EU-Russia Energy Relations. 2020. Available online: https://think.visegradfund.org/wp-content/uploads/Think-Visegrad-Paper-Aliaksei-Patonia.pdf (accessed on 26 December 2021).
125. Zabanova, Y.; Westphal, K. Russia in the Global Hydrogen Race. SWP Comment. 2021. Available online: https://www.swp-berlin.org/publications/products/comments/2021C34_Russia_Hydrogen.pdf (accessed on 26 December 2021).
126. Energy Iceberg China Fuel Cell "Subsidy" Policy: Game Plan Breakdown. Available online: https://energyiceberg.com/china-fuel-cell-subsidy-design/ (accessed on 25 November 2021).
127. Voigt, C.C.; Straka, T.M.; Fritze, M. Producing wind energy at the cost of biodiversity: A stakeholder view on a green-green dilemma. *J. Renew. Sustain. Energy* **2019**, *11*, 063303. [CrossRef]
128. Al-Qahtani, A.; Parkinson, B.; Hellgardt, K.; Shah, N.; Guillen-Gosalbez, G. Uncovering the true cost of hydrogen production routes using life cycle monetisation. *Appl. Energy* **2021**, *281*, 115958. [CrossRef]