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The Green Hydrogen Puzzle: Towards a German Policy Framework for Industry

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Abstract: Green hydrogen will play a key role in building a climate-neutral energy-intensive industry, as key technologies for defossilising the production of steel and basic chemicals depend on it. Thus, policy-making needs to support the creation of a market for green hydrogen and its use in industry. However, it is unclear how appropriate policies should be designed, and a number of challenges need to be addressed. Based on an analysis of the ongoing German debate on hydrogen policies, this paper analyses how policy-making for green hydrogen development may support industry defossilisation. For the assessment of policy instruments, a simplified multi-criteria analysis (MCA) is used with an innovative approach that derives criteria from specific challenges. Four challenges and seven relevant policy instruments are identified. The results of the MCA reveal the potential of each of the selected instruments to address the challenges. The paper furthermore outlines how instruments might be combined in a policy package that supports industry defossilisation, creates synergies and avoids trade-offs. The paper's impact may reach beyond the German case, as the challenges are not specific to the country. The results are relevant for policy-makers in other countries with energy-intensive industries aiming to set the course towards a hydrogen future.

Keywords: green hydrogen; climate-neutral industry; carbon dioxide emissions; policy package; multi-criteria analysis

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1. Introduction

Green hydrogen and hydrogen-based synthetic fuels will play a key role in a future climate-neutral world, as they will help defossilise processes and applications where direct electrification is not possible for technical or economic reasons.

In industry, hydrogen can be used to avoid process emissions and to decarbonise heat and steam production. Hydrogen may contribute to bringing emissions down to (almost) zero in this sector [1]. For instance, primary steel production can become almost climate-neutral via the direct reduction of iron with green hydrogen [2]. In the chemical industry, emissions can be reduced initially by replacing the hydrogen from fossil sources currently used in production processes with green hydrogen and, thereafter, by producing fuels and basic materials from synthetic feedstocks based on green hydrogen and non-fossil carbon sources. Further, green hydrogen can replace fossil fuels in the generation of high-temperature-process heat and steam [3].

Green hydrogen applications can also reduce emissions in the mobility, energy and transport sectors, for example as a decarbonisation option for air transport and shipping, to back-up electricity generation and to replace the natural gas used in combined heat and power generation in district heating systems [3–5]. Other green hydrogen applications, such as in cars and individual buildings, are possible but controversial, given the higher energy efficiency of solutions based on direct electrification [5].

Hydrogen can be produced through water electrolysis, which is associated with very low CO_2 emissions if the electricity used is generated from renewable energy sources (green hydrogen) (for a definition, see [6]). CO_2 emissions from fossil-based hydrogen production can be significantly reduced through carbon capture and storage (blue hydrogen or low-carbon hydrogen), but not to the extent of green hydrogen use. Other hydrogen-production processes, for instance methane splitting, are undergoing research and might also become relevant in the future.

The use of hydrogen for energy production is being intensely debated in Germany. Scenarios proposing a reduction in greenhouse gas (GHG) emissions of at least 95% by 2050 (relative to 1990) show that the demand for hydrogen and hydrogen-based synthetic fuels could reach substantial levels by mid-century, although results vary depending on specific assumptions. Several studies suggest that the yearly demand for hydrogen by 2050 could be up to 400 TWh [3,7], while the demand for hydrogen and hydrogen-derived synthetic fuels and feedstocks together could reach more than 800 TWh [4,8]. This would be a massive increase compared to the 55 TWh of mostly fossil-based hydrogen used in Germany per year today [9].

In Germany and elsewhere in the world, policy-makers and stakeholders have recognised the relevance of hydrogen. Many countries have already developed targets and strategies and are currently implementing policy instruments to support hydrogen [10]. In the EU and Germany, the European Hydrogen Strategy (EUHS) and the German National Hydrogen Strategy (NHS) both focus on green hydrogen and set targets for the development of electrolyser capacity for the next decade. By 2030, the European Commission envisages electrolyser capacity of 40 GW for Europe. The German government anticipates a capacity of 5 GW for Germany by the same date. Thus, significant domestic green hydrogen production is envisaged, although imports are still expected to cover a large share of the demand. As hydrogen technologies are not yet competitive, the two strategies agree that support policies are needed [9,11].

A discussion of the policy instruments required to support green hydrogen production and use has recently emerged [2,5,6,12–18]. Suggested policies include public support for investments, certification, Carbon Contracts for Difference (CCfDs), quotas for green hydrogen or hydrogen-based products, subsidies for green hydrogen production, electricity price reforms and infrastructure regulation. However, the appropriate design of policies and policy packages is still unclear and controversial.

This paper aims to contribute to the discussion by analysing whether policy instruments aimed at facilitating green hydrogen development are suitable for addressing the defossilisation needs of energy-intensive industries.

For this purpose, this paper first identifies the major challenges policy-makers face in creating a hydrogen system, and second, shows how policy instruments could help address the challenges. This is done by using a simplified multi-criteria analysis. Finally, it proposes short- and longer-term policy actions and discusses options for a policy mix.

It concentrates on domestic production and the use of green hydrogen from electrolysis in Germany while acknowledging that other types of low-carbon hydrogen may play a role in the future, at least in a transitional period. This paper leaves aside the manifold challenges of imports and the geopolitical implications of the global hydrogen trade (for a review, see Van der Graaf et al., 2020) [19]). While the German context is used as a case study in this paper, the method developed here is transferable to other countries, and the results are relevant for countries with energy-intensive industries facing similar challenges. As many countries are currently developing policy packages for hydrogen, the results of this analysis will support other countries in identifying barriers and implementing effective instruments.

2. Materials and Methods

The research aim of this paper is to identify key policy instruments in the field of green hydrogen in industry, which is widely discussed in reports and debates, and to evaluate them using a simplified multi-criteria analysis (MCA).

An MCA is suitable because a single-criterion approach would fail to account for the many factors involved and the complexity of building a hydrogen system. The criteria for evaluating policy instruments are derived from currently discussed challenges. Thus, the aim is to evaluate policy instruments according to whether they can help overcome existing barriers.

Criteria-based analysis of policies, policy packages and policy mixes is a common approach in research on energy and sustainability transformations, with standard criteria based on effectiveness, cost-effectiveness, political feasibility and the like (for instance [20–23]).

Another widespread approach in the analysis of transformation policies is to identify barriers for policymaking (see, e.g., the development of implementation strategies based on barriers [24], the identification of barriers to renewable energy development in Pakistan [25] and frameworks based on barriers to ratcheting-up climate policy [26]). The innovation in this paper is that barriers (here: challenges) are identified first and then translated into criteria for policy-making. This allows identifying the trade-offs that are specific to the case of industry-focussed hydrogen policy, which would not be captured by the standard criteria. Therefore, this method is closely related to and complementary to existing MCA approaches and barrier analysis.

Despite the novel character, the approach used in this paper is based on existing and established methods of MCA [27–30]. For this purpose, a step-by-step approach is used. All criteria are rated on a qualitative basis and have equal weighting. A sensitivity analysis is not done.

The process followed is:

1. Definition of the decision context.
2. Identification of policy options facilitating industrial hydrogen use.
3. Identification of criteria based on challenges.
4. Scoring.
5. Comparison of results.
6. Conclusion.

The first step of the MCA is covered in the Introduction (Section 1). The decision context includes the current development in Germany of a hydrogen economy from the point of view of energy-intensive industry. The publication of the NHS and other strategic documents provides the rationale for looking closely at this topic. We focus on domestic policy-making and exclude instruments related to imports and global markets, such as carbon border adjustments. These instruments require coordination at least on a European level, which is not addressed here. The target group is policy-makers who will be provided with guidance for future policy-making.

The second step is based on an analysis of literature (Section 3.1). Here, we examine which policy measures are being proposed by different actors (science, economy and politics). Since a large number of documents exist on the potential development of hydrogen, we carry out a semi-systematic review [31].

A greater focus is put on the third step, which identifies the key challenges policy-makers face in attempting to build a green hydrogen market (Section 3.2). This assessment is based on an analysis of relevant literature combined with the authors' participation in debates with key industry stakeholders and with observations of the national public debate. Meetings with stakeholders have taken place quarterly since April 2019 as part of the hydrogen working group IN4climate.NRW, a platform for the collaboration of industry, science and politics in North Rhine–Westphalia). Based on our material, we propose that current policy challenges can be grouped into four categories. These challenges are used in the further assessment of policy instruments. Since the purpose of this paper is to analyse whether policy instruments can help overcome major challenges, the challenges are translated into criteria for the MCA.

In the fourth step, each policy instrument is discussed and analysed through the lens of the MCA (Section 4.1). We examine whether and how each policy instrument addresses the criteria of our analytical framework and identify relevant design elements. In scoring, policy instruments are assessed according to the following principle:

- ++ very relevant for overcoming a challenge
- + relevant for overcoming a challenge
- (+) indirectly contributing to overcoming the challenges.

If a policy instrument is not suitable for addressing a challenge/criteria or if the challenge/criteria are not relevant, no assessment is made. Thus, only a positive assessment is made. We assess the policy instruments in a qualitative sense and have in-depth experience in the field of energy and climate policy from direct exchanges with stakeholders from different sectors. Furthermore, the assessment and feedback of two other senior experts in the fields of political science and the hydrogen economy are taken into account in the analysis.

The results are summarised and compared in a comprehensive and easy-to-read table (Section 4.2). The aim is to show whether all challenges are covered by different policy instruments, whether one instrument can address all challenges or whether a mix of policy instruments is necessary. Finally, we sketch potential policy strategies, combining them in a short- and longer-term perspective (Section 4).

3. Identification of Policy Options and Challenges

3.1. Policy Options Facilitating Industrial Hydrogen Use

This section covers the second step of the MCA by identifying, on the basis of a literature review (e.g., [2,5,6,15–17]), the most important policy instruments currently being most intensively debated.

- Certifying production methods and their environmental impacts: Guarantees of Origin (GOs) for hydrogen Certificates and GOs will play an important role in ensuring the environmental and social sustainability of a future hydrogen economy. By providing information about how the hydrogen is produced, they will create transparency about its environmental impacts. Where certificates create tradable financial value, they will stimulate ownership of these environmental attributes [6,32]. While GO systems for renewable electricity are long established, a universally accepted standard for green hydrogen does not exist. Approaches are being developed at the national and international level, but they differ in requirements regarding the electricity source, system boundaries of carbon accounting, emission thresholds at which hydrogen is classified as green and production technologies included. Different sustainability criteria beyond climate effects may apply, for instance, regarding the sustainable use of water resources or the effects of air pollution [6].
- Increasing the ambition of the European Union Emissions Trading System (EU ETS) Carbon pricing policies are meant to internalise the environmental costs of carbon dioxide emissions and make low-carbon energy more competitive. The existing EU ETS sets a cap on emissions from the European electricity sector, energy-intensive industries and aviation. In addition, at the beginning of 2021, a national ETS came into effect in Germany, covering fuel use in non-EU ETS sectors. A reform of the EU ETS was proposed by the European Commission as part of its ‘Fit for 55’ package. The further development of this instrument will significantly influence conditions for green hydrogen use by industry.
- Supporting green hydrogen production: reform of electricity charges and funding policies This instrument includes the reform of charges and financing policies, such as investment support for electrolysers, de-risking instruments and financing contracts for the production of certain quantities of green hydrogen [24]. The state financing of hydrogen production from electrolysis is an obvious option for policy-makers. In Ger-

many, the government initially addressed electricity fees and charges which—if fully charged on electrolysers—would make up a large share of the costs of domestically produced green hydrogen (see Section 3.2.1). Also, there could be direct state support for green hydrogen production. For instance, the government could auction funding for a certain amount of green hydrogen production [32]. The German government has announced that tenders for green hydrogen production will be examined through the NHS.

- Supporting hydrogen use: Carbon Contracts for Difference Funding may also be targeted at large users of hydrogen. This could create a stable demand for hydrogen and thus indirectly support the scale-up of green hydrogen production. CCfDs are currently being intensely debated as an instrument, in particular to close the difference in operating expenses (OPEX) for low-carbon breakthrough technologies (LCBT) [17,33]. Both the EUHS and the NHS envisage CCfD pilot programmes, particularly for the steel and chemical industries. Individual projects that implement LCBT could receive such a contract, which would guarantee a certain price for avoided CO_2 emissions (the 'strike price') for a certain period of time. As long as the strike price is higher than the current CO_2 price, the state would pay the difference to the firm.
- Promoting hydrogen by creating demand: quotas Quotas for hydrogen, hydrogen-based synthetic fuels or for materials produced using green hydrogen are options for creating a reliable market for plant manufacturers and thus triggering investment in hydrogen production [34]. Some actors have suggested a quota for green (or possibly blue) hydrogen or generally for renewable gases in the gas system [2,32,35,36]. Quotas could also be set for materials produced using green hydrogen, such as carbon-free steel, ammonia, methanol and other chemical products [34]. However, this option needs to be scrutinised very carefully for its effects on competitiveness in the global market for German and other European producers [37]. More realistic in the short term are renewable quotas for sellers of shipping and aviation fuels. The NHS discusses a quota of at least 2% renewable kerosene in the aviation sector by 2030, as this sector will be dependent on liquid fuels for the foreseeable future [9]. This has now been implemented through the national implementation of the Renewable Energy Directive.
- Crediting green hydrogen for renewables targets in the transport sector following the implementation of the EU's revised Renewable Energy Directive (RED II) RED II came into force in December 2018. Article 25 requires fuel suppliers to supply a minimum of 14% renewables by 2030 (up from 10% in the 2009 version of the Directive). Until now, this requirement has been met primarily by blending biofuels. The revised Directive allows suppliers to take into account 'gaseous transport fuels of non-biogenic origin also when they are used as an intermediate product for the production of conventional fuels' (Article 25). It is therefore permitted to count the GHG emissions saved by green hydrogen when using hydrogen to produce synthetic fuels or in the production of conventional fuels in refineries [38]. The fact that Member States can go beyond the minimum requirement in transposing the Directive has sparked heated debate in Germany where, at the end of 2020, the government set a target of 25% of the renewables share by 2030 [39].
- Regulating hydrogen grid infrastructure A transport and distribution infrastructure is required to enable the large-scale and widespread use of green hydrogen. Because legal certainty is a prerequisite for network operators and investors, establishing this infrastructure requires an adjustment of the regulatory framework at the national and European levels [40,41]. Currently, there are rules for blending hydrogen for use in natural gas networks, but in Germany, there is no regulation providing for a pure hydrogen grid infrastructure [12,42]. Through the European Green Deal, the EU recognises the importance of 'smart infrastructure' frameworks, such as hydrogen networks [43]. A revision of the European legal framework for energy infrastructure (for example, the Trans-European Network Energy Regulation) is envisaged in the context of the EUHS [11]. Germany's NHS is aiming to create a regulatory framework

for hydrogen infrastructure quickly, and in November 2020, the Federal Network Agency published the results of a consultation on the subject [42]. The consultation report reflects key grid-regulation concerns, which will influence the set-up of the hydrogen system as a whole.

3.2. Challenges for Policy-Making to Define Criteria

This section covers the third step of the MCA. It defines criteria for the analysis of the policy instruments identified in the last section. Since the policy instruments are to be analysed in terms of whether they are suitable for overcoming existing challenges, the challenges are first identified in order to derive criteria from them.

3.2.1. Creating Business Cases Despite High Costs

Green hydrogen production costs in Germany are much higher than those of fossil hydrogen production. Additionally, hydrogen-based industrial production processes are significantly more expensive than conventional production processes. These cost differences are expected to fall in the coming decades but currently represent a strong barrier to fast market development and the early use of green hydrogen by industry.

In Germany, green hydrogen can be produced for around 6 EUR/kgH_2 [44] and so cannot compete with blue and grey hydrogen, the costs of which, as a European average, are 2.1 EUR/kgH_2 and 1.5 EUR/kgH_2, respectively [45]. Current global production costs of green hydrogen from electrolysis depend largely on the production site and operating hours and range from 2.5 USD [46] to 6.5 USD/kgH_2 [47].

The price of green hydrogen is affected by factors such as high electricity procurement costs and high capital expenditures (CAPEX) for electrolysers (ranging from 1100 USD/kW to 1800 USD/kW for the currently favoured proton exchange membrane electrolysis (PEM) technology). In Europe, PEM is thought to be the most useful method due to its flexibility and simple scalability [45] in comparison alkaline electrolysis (AEL) and solid oxide electrolysis (SOEC). Increasing electrolysis efficiency, resulting in a reduction in specific electricity costs, and higher utilisation of the electrolysers (full load hours) will lower the CAPEX. This is expected to significantly lower green hydrogen prices in the long term.

Electricity prices have a major impact on hydrogen production costs. According to Gigler and Weeda (2018) [47], each 10 EUR increase in the price per MWh of electricity increases green hydrogen production costs by 0.5 EUR/kg. High electricity costs can prevent the scale-up of hydrogen production. To avoid this, Germany introduced exemptions from taxes and levies for green hydrogen production. The Renewable Energy Sources Act (EEG 2021) established an explicit exemption from the EEG surcharge for green hydrogen in early 2021. This reduces the cost difference between green and fossil-based hydrogen but will not remove it completely (Section 4.1.3).

Other, future cost reductions for hydrogen are expected to be achieved by technological development and scale effects in the production and use of electrolysers. It is expected that PEM-CAPEX will fall to a fraction of its current level within the next 20 to 30 years, to around 650 EUR/kW in 2030 and 300 to 500 EUR/kW in 2050 [14,48,49]. This will lead to an overall hydrogen production cost range of 3 to 5.7 EUR/kgH_2 in 2030 [44,47,50] and 1 to 2.9 EUR/kgH_2 in 2050 [50,51]. Between 2030 and 2040, average international green hydrogen production costs are expected to match those of fossil-based blue hydrogen with CCS in all cases [46].

Figure 1 shows cost differences between grey (fossil-based), blue (fossil-based with carbon capture and storage) and green hydrogen and possible future developments, as summarized by Bukold (2020) on the basis of different studies [45]. It illustrates that green hydrogen is not competitive today, but that its costs may approach the levels of grey and blue hydrogen by 2030 under optimistic assumptions and by 2050 under less optimistic assumptions.

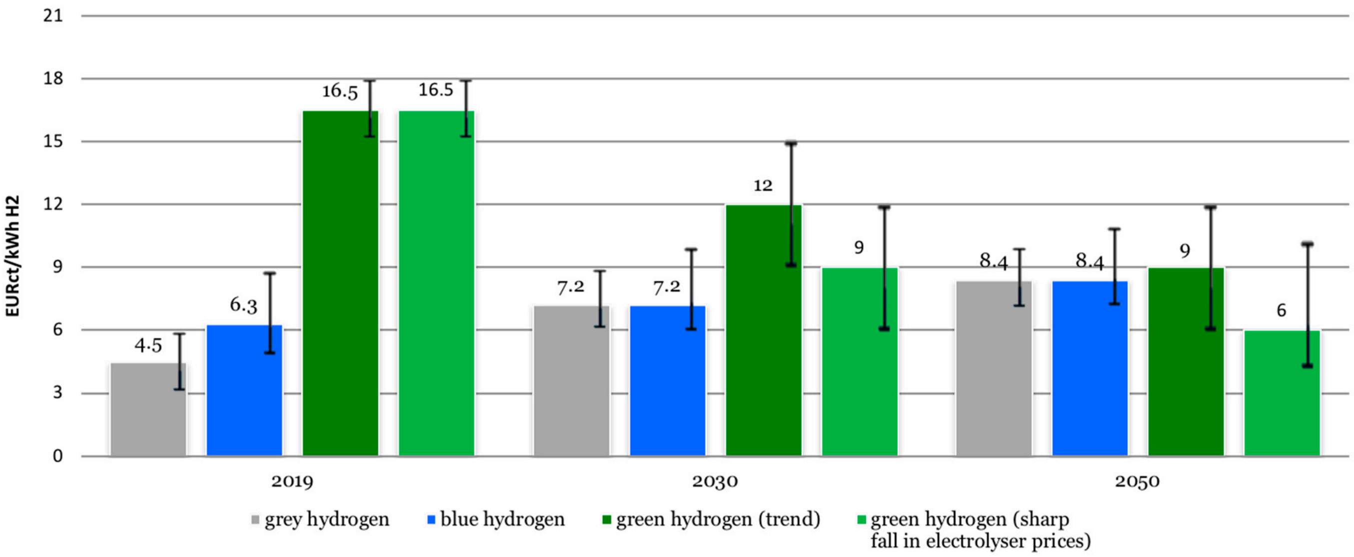

Figure 1. Production of hydrogen: costs and cost trends (in EURct/kWh H_2). Assumptions for 2030: CO_2 price 100 EURt, natural gas price remains stable. Assumptions for 2050: as for 2030 plus carbon import tax of EUR100/t CO_2. The black bars represent the ranges between values from different studies. Source: Bukold (2020).

The cost difference between green hydrogen-based technologies and conventional technologies based on fossil fuel resources may also affect the industrial use of green hydrogen. For instance, green hydrogen-based steel production is calculated to cost 730 EUR per tonne of crude steel, whereas production in conventional blast furnaces costs 475 EUR per tonne [52]. Although the investment costs are also higher, the difference is largely due to the cost of hydrogen (here assumed to be 140 EUR/MWh). This cost difference is a significant barrier to early investment in these new technologies. Therefore, this challenge is used as a criterion for the analysis of hydrogen policy (see Table 1).

Table 1. Challenge and criterion #1 for hydrogen policy.

Challenge #1	Criterion #1
The investment and operational costs (CAPEX and OPEX) of the production and usage of green hydrogen are still high and green hydrogen is not yet competitive. Electricity prices and the electrolyser CAPEX drive up domestic green hydrogen-production costs.	The policy mix supports the creation of business cases and the reduction in the cost of green hydrogen production and industrial applications and allows for fast market development. It accounts for the difference in cost between green hydrogen and fossil-based hydrogen and between green hydrogen and fossil alternatives in specific applications.

3.2.2. Ensuring Climate-Friendly Production of Green Hydrogen

For hydrogen-based defossilisation of energy-intensive industries to be credible, the electrolytic production of hydrogen must not indirectly cause CO_2 emissions. Hydrogen from electrolysis is climate-friendly only when produced using electricity from renewable sources. When using the current German electricity mix, in which renewables contribute less than 50% [53], electrolysis causes higher emissions than conventional hydrogen production through methane steam reforming [45].

One option is to only use surplus electricity from renewables. Electrolysers located in regions with high renewable electricity production could be operated when excess electricity cannot be integrated into the grid. However, this would not fully compensate for investment and operation costs. The profitability of electrolysers increases with the number of full load hours [44], and at least 3000 to 4000 full load hours are necessary for electrolysis to be economically viable [54].

In the case of operation with higher full load hours, renewable electricity could be allocated to electrolysis through the purchase of green electricity certificates, which would formally allow the production of green hydrogen. However, in this case, there would be no physical or temporal coupling of green electricity and green hydrogen production. While the green electricity would be allocated to hydrogen on the balance sheet, fossil use would increase for other electricity uses and, overall, fossil power production might even increase to meet the additional electricity demand [55]. Moreover, operation with high full load hours would not provide the co-benefit of helping to stabilise the electricity system with increasing shares of fluctuating renewable sources.

In summary, the electrolytic production of green hydrogen is only effective ecologically if the electricity used is provided by surplus renewable electricity or electricity from *additional* renewable production capacity. This additionality ensures that electricity-based hydrogen production does not merely lead to a relocation of CO_2 emissions from one sector to another [54,55]. Thus, further expansion of renewables is essential in Germany to ensure the climate-friendly production of hydrogen. Table 2 translates this challenge into a criterion.

Table 2. Challenge and criterion #2 for hydrogen policy.

Challenge #2	Criterion #2
Ensuring the climate-friendly production of green hydrogen. Green hydrogen will only contribute to emission reductions if renewable energy generation capacity is expanded correspondingly or if surplus electricity is used.	The policy mix ensures that the expansion of hydrogen brings about emission reductions—which means that the production of renewable energy needs to increase correspondingly. Either excess or additional renewable energy should be used for the production of hydrogen. It also sets incentives for electrolysers to be built at locations and operated in a way that is compatible with the needs of the electricity system.

3.2.3. Securing Access to Green Hydrogen for Priority Applications

There are numerous possible applications for green hydrogen. However, in the foreseeable future supply will be limited. The German government is struggling to fulfil national targets for renewable energy expansion already without considering additional capacities for green hydrogen production. Other countries face similar challenges, and a global hydrogen market will take time to develop. Thus, the question arises as to where the limited green hydrogen should be used first [5] and how policy-making can support priority applications.

In industry, the use of green hydrogen can lead to significant emission reductions, particularly in new production processes in the steel and chemical industries but also when used to produce high-temperature heat and steam [3,5]. In many cases, there are no, or no appropriate, alternatives to the use of hydrogen for defossilisation. Where green hydrogen replaces fossil hydrogen in existing processes, such as ammonia production or refineries, existing assets and infrastructure may be used [9] and the application of green hydrogen may already be a profitable option. However, hydrogen-based LCBT for green steel production or the production of non-fossil chemical products is associated with high costs (Section 3.2.1) and with large-scale investment in long-lived assets. This investment should take place early to avoid being locked into conventional production processes for further decades.

Some applications of green hydrogen and hydrogen-based synthetic fuels in the transport and power sectors may also qualify as priority applications. There are few alternative low-carbon options available for maritime shipping and aviation [15]. For heavy-load road transport, commercial vehicles and public transport, the use of hydrogen competes with other options [56]. Furthermore, the energy and building sectors may use green hydrogen in the future and some studies see a significant role for hydrogen in fuel cell-based cogeneration [3,4,57]. The use of green hydrogen in private cars and individual buildings is advocated by some stakeholders but would be hard to justify in the face of limited supply since more efficient solutions (e.g., direct electrification) exist.

Given that only a limited amount of green hydrogen will be available in the coming decades it should be channelled first to areas without viable decarbonisation alternatives and where long-term investment decisions may depend on green hydrogen availability. Policy-making can influence the conditions for different uses and thus should set strategic priorities and incentives (see Table 3).

Table 3. Challenge and criterion #3 for hydrogen policy.

Challenge #3	Criterion #3
Due to the limited supply of green hydrogen, there is a competitive situation between different users that may prevent planning security and delay investments or lead to non-optimal use of the limited hydrogen available.	The policy mix sets clear priorities and promotes investment security. Support should focus on users who have no viable alternative to the use of hydrogen for achieving climate neutrality, and on applications that can achieve large emission reductions in the long term but require investment decisions today.

3.2.4. Building a Transport Infrastructure

Today, long-distance transport infrastructure for hydrogen is almost non-existent, as the grey hydrogen currently used in industry is usually produced on-site or only transported via regional grids. However, increased hydrogen use in the future will require infrastructure that connects producers and consumers [58].

In principle, several transport options and combinations of options are conceivable; which one is used will depend on existing infrastructure and regulations, the demand profile, the distance, CAPEX and OPEX and the acceptance of different actors [59,60]. These options include the transport of hydrogen by truck in gaseous or (for longer distances and large quantities) liquid form [61]. As an alternative, hydrogen can be transported by ship or rail, provided that suitable waterways, railways and loading terminals are available [59].

Pipelines will probably be needed for the large-scale use of hydrogen. One option is to add hydrogen to the natural gas network. However, hydrogen blending is subject to restrictions; in Germany, for example, the limit is 10% by volume [62].

Since many industrial consumers require pure hydrogen for their facilities and decarbonisation processes, it will be necessary to build a separate hydrogen network linking hydrogen production sites with demand centres.

A number of European gas grid operators propose to build a large-scale pure hydrogen network mainly by converting existing gas pipelines and partly building new pipelines [63].

Thus, the challenge for policy-making is to enable the long-term organisation and coordination of infrastructure planning in the face of considerable uncertainty regarding the geographical distribution of hydrogen production and hydrogen demand. That is why the challenge was translated into a criterion for the analysis of policy instruments (see Table 4).

Table 4. Challenge and criterion #4 for hydrogen policy.

Challenge #4	Criterion #4
Building up transport infrastructure. The current infrastructure is not sufficient to connect prospective producers and consumers.	The policy mix sets clear priorities and promotes security for investments. Support should focus on users who have no viable alternatives to the use of hydrogen for achieving climate neutrality and on applications that will achieve large emission reductions in the long term.

4. Results

4.1. Analysing and Scoring the Policy Instruments

4.1.1. Certification and GOs for Hydrogen

GOs have a clear focus on one criterion. In this analysis, the instrument exclusively helps guarantee the climate-friendly production of green hydrogen (Criterion #2). To date, however, there is no internationally used and accepted standard.

In Germany, a standard for green hydrogen exists that labels hydrogen from electrolysis as green only if electricity from renewable sources is used [64,65]. At the European level, the multilateral project CertifHy establishes a supra-regional certification system for hydrogen. The system covers green and low-carbon hydrogen, the latter including blue hydrogen and pink hydrogen produced by electrolysis using nuclear power (www.certifhy.eu, last accessed 10 November 2021). CertifHy focuses on the mechanisms for a system of tradable GOs. The definition of sustainability and GHG reduction criteria for green hydrogen production, including the criteria for electricity sources, is being developed in the context of RED II. This directive requires that electricity-based hydrogen or synthetic fuels (RFNBOs) achieve a greenhouse gas reduction of at least 70% compared to the fossil fuel baseline and that the electricity has a renewable origin [38].

To guarantee that green hydrogen is actually used and that the additional expansion of renewable energies is triggered, a preferably internationally accepted system is necessary. Through the integration of the additionality criterion in standards for green hydrogen and GO, the instrument influences which level of net GHG reduction at a system level is achieved. This is important to achieve national climate targets and to ensure that there are no negative impacts on the development and scale-up of other climate-friendly technologies due to a lack of renewable electricity supply. Because the instrument is so relevant for renewable energy development, the instrument is rated + + for this criterion, although the design is still not fully clarified.

4.1.2. Carbon Pricing/EU ETS

ETS supports the creation of business cases for climate-friendly products and technologies (Criterion #2). However, today, ETS allowance prices are not sufficiently high to cover the additional costs of green hydrogen production and hydrogen-based low-carbon technologies in industry [2]. Generally, despite significant recent increases in allowance prices, their development still does not reflect a cost-effective pathway. This is also due to policy and market uncertainties, which prevent the ETS from creating sufficient long-term investment certainty [66]. However, recent reforms have significantly increased the stringency of the EU ETS [67], and in July 2021, the European Commission with the "Fit for 55"package, proposed to cut emissions faster and stronger in the future through the EU ETS.

The system of free allocation to industry in the EU ETS, which exists to prevent carbon leakage, currently reduces the CO_2 price signal for hydrogen-based low-carbon breakthrough technologies in industry. With current allocation rules and benchmarks as defined for the fourth trading period [68], low-carbon industrial production may at least, in some cases, receive significantly fewer free emission allowances than conventional production. Without free allocation, the CO_2 cost difference would create an advantage for low-carbon production technologies compared to conventional technologies, which could compensate for the higher production costs of these technologies. However, as long as conventional production receives allowances for free (while new installations with very low emissions do not), such a cost difference will not, or at least not fully, come into effect.

One solution is to replace free allocation with other measures that guarantee an international level playing field and prevent carbon leakage, for instance, a carbon border adjustment mechanism as proposed by the European Commission in July 2021 [69] or stronger international coordination of carbon policies [70]. Another remedy could be to change allocation rules so that climate-friendly production receives as many emission certificates as conventional production. However, this may not be sustainable in the long term with the EU ETS cap on emissions decreasing towards zero [37].

In summary, further developing carbon pricing policies can play a key role in reducing the cost gap between low-carbon and conventional fuels and technologies (Criterion #1). For this, the ambition of policies must be enhanced in line with the target of climate neutrality by 2050, and reforms need to ensure that the CO_2 price signal is not distorted for industrial LCBT. The instrument is rated + for the criterion because it can create business cases, but the necessary reforms are politically challenging and are unlikely to come about quickly.

4.1.3. Reform of Charges and Funding Policies

As the name suggests, this instrument addresses Criterion #1 as it reduces the cost gap for industry actors. At the end of 2020, the German parliament introduced exemptions from the EEG surcharge (the charge on electricity that finances the remuneration paid to renewable plant operators) for electrolysers producing green hydrogen. In June 2021, a regulation was adopted defining the specific requirements enabling green hydrogen to benefit from the exemptions. These requirements are less strict than those proposed by the European Commission in the context of RED II (Section 4.1.6) but will have to be adjusted to European legislation in the future.

This exemption will significantly reduce the cost of green hydrogen production in Germany. Therefore, the instrument is rated + for Criterion #1. However, since it reduces hydrogen costs for all potential applications, it may create disadvantages for more efficient and direct uses of renewable electricity in some sectors, such as power-to-heat solutions. Thus, the exemption for green hydrogen production needs to be embedded in more comprehensive reforms of the system of fees and charges to create equal conditions for direct electrification.

Other financing instruments, such as the investment support for electrolysers, can also help reduce the cost gap. Depending on the design of the instrument, a greater or lesser contribution can be made here (+ or ++).

In summary, exemptions from electricity taxes and charges reduce OPEX for electrolysis and reduce the cost gap between green and fossil-based hydrogen, and thus support the creation of business cases. However, selective exemptions must not create disadvantages for direct electrification strategies. Furthermore, as exemptions shift costs to other electricity users, distributive consequences must be taken into account.

Exemptions and funding policies for green hydrogen production can also be designed to support the climate-friendly production of hydrogen (Criterion #2) by defining corresponding requirements and standards for eligible hydrogen production plants. Since the effect is still very unclear, it is rated +, which means an indirect effect.

4.1.4. Carbon Contracts for Difference

CCfDs close the cost gap resulting from CO_2 avoidance and eliminate the risk resulting from uncertain and fluctuating CO_2 prices, which improves financing conditions for investments. They can level out differences between green hydrogen or hydrogen-based industrial production processes and their conventional alternatives and thus indirectly create a significant and stable demand for hydrogen (Criterion #1). Therefore, the instrument is rated ++ for this criterion.

CCfDs that cover the gap between the strike price and ETS allowance prices require the CO_2 price to partly cover the cost gap between LCBT and conventional production—which may not be the case due to free allocation rules (Section 4.1.4). If they do not, contracts could be designed to cover the full avoidance costs. However, as a subsidy-type instrument, they carry the risk of creating high costs for the state or consumers.

The instrument's mechanism for determining the strike price is as yet undetermined. OPEX of hydrogen-based LCBT and thus their CO_2 avoidance costs are influenced by several factors, including prices for green hydrogen. If these costs deviate strongly from what is anticipated when the strike price is determined, the contract could either generate windfall profits for the firm or insufficiently cover avoidance costs. A more dynamic design of CCfDs may be a remedy but will also increase the instrument's complexity.

This instrument addresses Criterion #1 and facilitates access to green hydrogen for priority applications (Criterion #3). By targeting individual technologies or industry branches, governments can state which uses of hydrogen are considered a priority. That is why the instrument is rated ++.

In addition, CCfDs may indirectly facilitate the development of transport infrastructure (+). If investment security is created for large industrial users, this might enhance the chances of, for instance, the required pipeline being built.

4.1.5. Quotas

Proponents argue that emission reductions achieved by a quota can be predicted relatively precisely and that substantial amounts of green hydrogen can thus be brought to the market [2].

Quotas or targets may lead to an increase in the amount of hydrogen or hydrogen-based fuels or materials in the market over time, thus supporting business cases for hydrogen producers with few administrative costs for the state [2]. Thus, the instrument addresses Criterion #1.

However, quotas may not provide investment security for industrial hydrogen users as prices could still fluctuate, and they may create competitiveness concerns on the global market. This instrument is therefore rated + with regards to Criterion #1.

A quota may channel green hydrogen to specific uses if it is introduced in a specific sector. A quota for kerosene in the transport sector, for instance, might help to guarantee the use of green hydrogen in areas where there are no alternatives for GHG mitigation. At the same time, quotas could be detrimental if they favour inefficient hydrogen use, such as synthetic fuels for private mobility. Quotas in the gas system, if introduced early, might lead to large amounts of scarce green hydrogen being blended for use in the natural gas grid and thus being drawn into heating. This may not be the preferred option from a systemic point of view and could postpone investment into more efficient options for decarbonising the heat sector, such as direct electrification. A general gas quota might consequently make sector targeting more difficult. Conversely, a specific quota for green hydrogen-based materials (steel and kerosene) might have a positive effect on Criterion #3.

The instrument also addresses some criteria indirectly (+). Whether a quota can boost renewable energy expansion depends on the increase of the target and the underlying definitions of green hydrogen (Criterion #2), and specific transport infrastructure may be needed for the steel industry, for example (Criterion #4).

4.1.6. Crediting Green Hydrogen for Renewables Targets in the Transport Sector in the Context of RED II Implementation

Crediting green hydrogen for renewables targets in the transport sector via RED II implementation has been included here because it has been intensively discussed in Germany and (compared to other instruments) can be implemented in the short term. Due to the climate requirements of the transport sector and the limited existing experience with hydrogen use (hydrogen filling stations and existing structures in refineries), the transport sector could achieve a fast market scale-up of hydrogen in the near future. Therefore, the national implementation of the relevant provisions of RED II (Section 3.1)—allowing green hydrogen to be credited for renewables targets in the transport sector—is a relevant instrument in this context.

The instrument is discussed as an option to address the cost challenge and to create a business case for green hydrogen (Criterion #1). Since the use of green hydrogen to avoid CO_2 emissions from refineries is close to economic viability, the implementation of RED II may help create demand and thus a business case for green hydrogen production. The instrument might thus ensure the demand for hydrogen, with little additional financial burden for society. Therefore, Criterion #1 is rated ++.

The instrument is focused on the transport sector and is likely to draw hydrogen into fuel production. RED II also contains a quota for green kerosene, which contributes to securing access for aviation as a priority application (Section 3.2.3). However, it also supports other applications, such as conventional fuel production, hydrogen and synthetic fuel use in any vehicle. On the one hand, this could have a rapid and significant effect on GHG reductions in the transport sector [38,71]. On the other hand, the use of green hydrogen for conventional fuel production and synthetic fuels could prolong the use of fossil fuels and combustion engines in private cars, and thus hinder investment in electric mobility, which is much more energy-efficient. At the same time, the large-scale use of hydrogen, in particular for hydrogen-based synthetic fuels, may reduce the availability of green hydrogen for priority applications, such as energy-intensive industry, as long as supplies are limited. Thus, the instrument does not unambiguously contribute to securing access for priority applications (Criterion #3).

Regarding transport infrastructure (Criterion #4), RED II can be implemented quickly without great effort. The required processes are already in place (in desulphurisation) and the use of hydrogen could be upscaled. The instrument may have an indirect effect on the transport infrastructure (Criterion #4) if green hydrogen used in refineries is not produced on-site (+). Via the underlying definition of green hydrogen (Section 4.1.1), the instrument may have an indirect effect on Criterion #2.

4.1.7. Regulating Grid Infrastructure

So far, many aspects of setting up a grid infrastructure are unresolved and need to be clarified before concrete measures can be implemented. For instance, should regulation focus on blending hydrogen into natural gas networks or on creating pure hydrogen pipelines? Are the existing rules on access, fees and unbundling for natural gas also suitable for hydrogen? Should there be priority grid access for green hydrogen? How should the hydrogen grid be financed?

Although the concrete design of the policy is unclear, the instrument does aim to build and support a grid infrastructure (Criterion #4). Clarifying issues and building a regulatory framework are the prerequisites for enabling the creation of a hydrogen infrastructure. Current efforts are aimed at integrating the needs of prospective producers and users of hydrogen. Due to the relevance of the secure legal framework, the instrument is rated ++.

The design of the regulation also relates to other criteria. The financing framework will affect costs for users and, if subsidies are considered, also for the state (Criterion #1). Significant investment in hydrogen pipelines may be possible if hydrogen is integrated into the existing regulatory and institutional framework for natural gas without increasing current gas grid fee levels. In this case, costs would be passed on to natural gas grid customers [12].

The instrument may also influence the prioritisation of hydrogen use. A focus on blending hydrogen would favour hydrogen use in buildings, while a focus on pure hydrogen could benefit industrial users (Criterion #3).

However, since only a few industrial hydrogen users would benefit from the emerging grid, at least in the short term, key actors do not support integrating hydrogen grids into the existing institutional framework for natural gas transport and instead propose financing according to the user pays principle [42,72].

For Criteria #1 and #3, only indirect effects can be assumed here (+).

4.2. Comparing the Results

In attempting to realise the potential of green hydrogen to transform energy-intensive industries, policy-makers face numerous challenges. Policy instruments can address these challenges from different angles. In this paper, we analysed a number of policy instruments and assessed whether they can address the challenges. We derived criteria from the challenges and analysed the instruments using a simplified MCA, and assessed whether an instrument is very relevant, relevant or indirectly relevant to address a certain challenge. Table 5 summarises the results.

Table 5. Summary of the Multi-Criteria Analysis.

Challenge/Criterion	#1 Creating Business Cases	#2 Ensuring the Climate-Friendly Production of Green Hydrogen	#3 Securing Access to Green Hydrogen for Priority Applications	#4 Building Transport Infrastructure
Certification and Guarantees of Origin		++ (defines requirements)		
Carbon pricing/EU ETS	+ (reduces the cost gap, effect depends on the price)			
Reform of charges and funding policies	++ (reduces the cost gap)	(+) (via certification/definition)		
Carbon Contracts for Difference	++ (guarantees the closure of the cost gap)		++ (industry)	(+) (possibly indirectly)
Quotas	+ (reduces the cost gap)	(+) (via certification/definition)	+ (if focused on specific markets)	(+) (possibly indirectly)
Crediting green hydrogen for renewables target in transport (RED II)	++ (secures demand)	(+) (via certification/definition)		(+) (possibly indirectly)
Regulating grid infrastructure	(+) (affects transport costs)		(+) (if pure hydrogen transport is supported)	++ (enables infrastructure development)

Note: ++ very relevant for overcoming a challenge, + relevant for overcoming a challenge, (+) indirectly contributing to overcoming the challenge. The specific effects depend on the design of the instrument.

The analysis shows that no instrument addresses all challenges equally, although some have an impact on several challenges. Most instruments have a clear focus on one challenge and are designed to address and overcome it. Some examples are GOs, which have a clear focus on the climate-friendly production of green hydrogen, and the EU ETS, which addresses Criterion #1—the creation of business cases.

In some cases, instruments focus on more than one challenge, such as in the implementation of CCfDs, which tackles Criterion #1, the creation of business cases, and Criterion #3, the prioritisation of hydrogen use. Quotas also address these criteria. Furthermore, some instruments have an indirect effect on different challenges. Here, the instrument is designed in such a way that it addresses a specific challenge directly and has an indirect impact on other challenges.

This makes it clear that the different instruments must be well coordinated so that they reinforce rather than negatively affect each other. This is particularly so with Criterion #1, for which several instruments are available. However, these instruments differ in their effects on the prioritisation of uses (Criterion #3), effects that are very relevant when choosing or combining instruments. Additionally, funding instruments need to be streamlined to avoid replicating support. With respect to the EU ETS, carbon prices are still insufficient to enable investment in key hydrogen-based technologies in industry and to prevent unwanted developments with respect to Criteria #2 and #3; additional policies will be necessary. Furthermore, CCfDs need to be coordinated with other instruments, such as exemptions from taxes, charges and funding for hydrogen production, to avoid double funding.

Certification is a crucial instrument for Criterion #2 and is a prerequisite for many other instruments. Although other instruments have an indirect effect on ensuring the climate-friendly production of green hydrogen, GOs are the only instrument with a clear focus on Criterion #2.

CCfDs are a key instrument for the early channelling of green hydrogen to priority applications in industry. Other instruments, in particular quotas, can also be designed to focus on specific sectors or technologies.

The fourth criterion is also clearly covered by one instrument, the regulating grid infrastructure, and only a clear regulation can create legal certainty, which is a prerequisite for the expansion of grids. Three other instruments have an indirect influence on this challenge.

In conclusion, only a comprehensive policy package can address all challenges—there is no one-fits-all solution—and to overcome all challenges, the instruments must be well coordinated. This is crucial in terms of time and to examine which instruments should be implemented in the short, medium and long term, and how the instruments, which are staggered in time, build upon each other.

5. Discussion

The MCA makes it clear that a policy package that combines different instruments is needed to address all challenges. The instruments should be well coordinated so that they reinforce each other in the best possible way. Furthermore, the interactions between the different instruments should be carefully considered. For instance, the certification of hydrogen is a prerequisite for most other instruments, and there are clear interactions between carbon pricing/EU ETS and quotas, and CCfDs and funding programmes.

In addition to designing a well-balanced policy package, it is crucial to take the right steps at the right time. Trade-offs may occur between the aims of enabling market development early enough to prepare for the transition and ensuring the long-term sustainability of the hydrogen system. A strategy is needed to address this conflict that kick-starts market development in the short term while implementing policies for a longer-term transition.

An important first step is to ensure favourable conditions for investments in early hydrogen production and use projects and nucleus infrastructure. This can be done (and has already been done in Germany) through an exemption from electricity charges for electrolysers, to make green hydrogen competitive, although effects on the electricity system and other actors paying the charges need to be monitored. Tapping the potential of transport sector demand, which in the German case is done through RED II, can also support a market ramp-up in the short term. However, care should be taken to not lock in the large-scale use of synthetic fuels in private road transport, where direct electrification is a much more efficient option, and to ensure the availability of green hydrogen for priority uses in industry. Furthermore, to facilitate early measures for infrastructure development, regulatory barriers should be addressed as soon as possible.

For industry, it is crucial that policies enable early investment in large-scale and long-lived applications for hydrogen use. For this, support programmes targeted at industry, such as CCfDs, should be a priority. Creating a reliable and strong long-term carbon pricing signal should be a key element of the policy strategy since this can create a level playing field for hydrogen that allows the phasing-out of support. Quotas might also be considered to channel hydrogen into specific markets. For the long-term sustainability of hydrogen production and the credibility of its users, stringent standards in green hydrogen certification, in particular concerning the additionality of renewable electricity, are a prerequisite. These standards may be gradually raised during the market development phase. In the long term, targets for climate-friendly materials or production standards could replace funding programmes [37].

The results of this paper are relevant for German hydrogen policy design but also for other countries with energy-intensive industries currently discussing and implementing policy measures for the development of a hydrogen market. Many countries have already published targets and strategies and are currently developing a policy package to promote (green) hydrogen. The World Energy Council (2020) [10] recommends a policy mix consisting of research and development, regulatory measures, financial support, acceptance and training and governance. However, the concrete design of the policy measures depends on national circumstances and existing challenges. Therefore, the approach from this paper can be used by policy-makers and transferred to other countries by first identifying the main challenges and by implementing policy instruments that address these challenges. The interactions between the instruments should also be closely examined. For future research, one question could be how certain types of challenges (e.g., priority uses of hydrogen) are tackled and overcome in different country settings (e.g., Netherlands, Japan and Australia in contrast to Germany).

While this paper has shown how different instruments may overcome central challenges to hydrogen development, more research is needed to deliver more robust policy recommendations. A cross-country SWOT analysis (strengths, weaknesses, opportunities and threats) of existing policy landscapes could help derive illustrative lessons relevant to Germany and beyond. Additionally, the list of challenges might be expanded, for instance by analysing internal barriers within businesses (e.g., hiring new staff) or the role of a hydrogen transition for structurally disadvantaged regions. Furthermore, in this paper, a simplified MCA without a sensitivity analysis was carried out, which represents a limitation to the granularity of the results. Further development of the analysis presented here could overcome these limitations by conducting a deeper MCA that achieves more extensive and robust results.

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