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LETTER

A sustainability and governance index for assessing the EU's green hydrogen import options

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Abstract

The European Commission's REPowerEU plan set the target of importing 10 million tonnes of 'green' hydrogen into the European Union (EU) by 2030. Against this backdrop, this paper sets out to assess a central question: which countries can be identified as suitable partners for European green hydrogen imports? Using Germany as a reference case, the article develops a quantitative sustainability and governance index (SGI), assessing five dimensions identified as central to ranking external partners: (i) the political will to scale up a green hydrogen sector; (ii) a country's integration with the EU/Germany; (iii) its commitment to international engagement and climate targets and policies; (iv) environmental regulatory effectiveness; and, (v) its governance performance. With this, the SGI offers a novel way of thinking about potential EU green hydrogen partnerships. Rather than focusing on the geography of renewables or cost structures underpinning a country's export potential, the present index captures the extent to which countries may be suitable for green hydrogen partnerships if judged by political and environmental factors. The empirical analysis suggests significant differences between a total of 113 assessed countries as per their overall index ranking, but also the individual dimensions composing the index. This allows drawing conclusions on the policy focus of potential partnerships, taking choices when facing trade-offs regarding individual dimensions, and prioritizing among the latter.

1. Introduction

On 18 May 2022, the European Commission announced an ambitious 'Plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition' (European Commision 2022a). Dubbed REPowerEU, the move came against the backdrop of Russia's war in Ukraine and set the target of 10 million tonnes of 'green' hydrogen imports into the EU by the year 2030, in addition to another 10 million tonnes produced at home (European Commission 2022d). Prior to this geopolitical shift, green hydrogen had been discussed as a possible remedy for hard-to-decarbonize sectors such as heavy industry and transport. Hopes were high that green molecules would become a climate-neutral energy carrier for a clean energy future, using renewables to split water into oxygen and hydrogen through electrolysis. Russia's aggression propelled green hydrogen to the top of policy agendas, now also nurturing hopes of ending dependence on Europe's formerly dominant energy supplier.

The overall volumes eyed by the European Commission are staggering. Amounting to some 330 terawatt hours (TWh), the EU 2030 target for both domestic production and imports respectively is roughly equal to the UK's total electricity consumption in 2021. In light of this, the Commission's 2020 Hydrogen Strategy (European Commission 2020), together with the 2022 'hydrogen accelerator' (European Commission 2022b) are hoped to ensure a rapid build-up of electrolysis capacity at scale. Yet, ambitious targets and policies notwithstanding, large-scale imports are quite likely, judged

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by the future demand as projected in pertinent EU strategies. Therefore, the European Union as well as its member states have enacted various high-level initiatives aimed at establishing clean energy partnerships with potential green hydrogen supplier countries. These partnerships either come in the shape of agreements on green energy sources more generally or are solely focused on green hydrogen production and export (European Commission 2022c, BMWK 2022).

EU-level initiatives aligned with the 2022 EU External Energy Strategy include the Green Partnership with Morocco, the EU-Egypt Renewable Hydrogen Partnership (which is eyed to evolve into a Mediterranean Green Hydrogen Partnership), or the Africa-EU Energy Partnership, viewed as a vehicle to foster an envisaged green hydrogen partnership between both continents (Bhagwat and Olczak 2020). National-level examples include Germany's 'hydrogen alliance' with Canada, its 'hydrogen accord' with Australia, as well as emerging partnerships with Namibia, Saudi Arabia or Norway (the latter focused on blue, that is low-carbon-hydrogen from natural gas before eventually switching to green sources later). Other EU member states such as the Netherlands are eying Morocco or Chile in their quest to secure imports.

Production costs are a central driver of concluded or planned partnerships (in addition to transport costs). It is therefore no surprise that the first external partnerships struck by European players include Morocco and Norway but also Namibia, that is countries that are assumed to produce green hydrogen at comparably low supply cost, thanks to a vast domestic renewable energy potential (Nunez and Quitzow 2023). Yet, as the 2022 energy crisis has driven home, the choice of external suppliers can no longer be a function of mere economic competitiveness (Goldthau and Sitter 2022). Instead, it is imperative to factor in the possible political costs of import choices. The EU's predominant focus on affordable energy supplies, notably from Russia, ended up neglecting the security risks arising from lopsided dependency structures.

Moreover, against the backdrop of the climate crisis, sustainability aspects play an important role in choosing external suppliers. Clearly, there are significant environmental risks associated with the production of green hydrogen. A water-intensive technology, green hydrogen may impact vulnerable ecosystems in producer countries, and potentially also freshwater resources for local communities. Land-use change may affect rural populations and their habitat. And renewable energy used for export-oriented hydrogen may not be available for decarbonizing energy systems in the producer countries (Heinemann *et al* 2021). Short of factoring the political and environmental costs into the choice of green hydrogen suppliers, the EU may end up repeating past mistakes by at the same time running counter to the principles it defined for rendering external hydrogen partnerships sustainable (European Commission 2022b).

This paper sets out to assess a central question: which countries can be identified as suitable partners for European green hydrogen imports? Using Germany as a reference case, it systematically ranks possible partner countries according to objective criteria, by way of empirically assessing pertinent political and environmental factors. To this end, the article develops a quantitative sustainability and governance index (SGI), aimed at ranking countries (see Böhringer and Jochem 2007) for EU green hydrogen partnerships.

The empirical focus on Germany is, on the one hand, a function of the country's historically high import dependency on Russian gas which in the wake of the Ukraine invasion prompted significant efforts by the German government to shift to non-fossil energy sources, including green hydrogen. By extension, the country is emerging as a significant player in the green hydrogen sector. Its domestic demand is forecasted to amount to between 95 and 130 TWh by 2030, only parts of which will be covered by some 10 GW of national electrolyzer capacity the government aims for by 2030 (BMWK 2023). This leaves Germany with significant import needs. On the other hand, the choice is analytical: assessing and ranking trading partners in commodities like green hydrogen requires data typically available at the national level, including existing trade partnerships. As Europe's largest economy, Germany therefore serves as a reference case for assessing the EU's options more generally.

The methodology underpinning the index deviates from existing studies primarily assessing the potential of green hydrogen across the world. A study by Lenivova (2022), for example, looks into the potential development of renewable hydrogen imports to Europe focusing on renewable energy potential, costs, maturity of natural gas infrastructure, proximity to hydrogen demand centers among other factors. A report by the Hydrogen Council (2020), by contrast, assesses the path to hydrogen competitiveness based on costs, while research by Brändle *et al* (2021) estimates the long-term global supply for low carbon hydrogen based on production and transport costs to countries like Germany, among others. Rather than focusing on the geography of renewables or cost structures underpinning a country's export potential, the present index captures the extent to which countries may be suitable for green hydrogen partnerships if judged by political and environmental factors. It can therefore help determine whether countries holding promising potential may indeed also be a desirable partner if sustainability and regulatory prowess are factored in. As we will further detail in the discussion, this may be done by contrasting and comparing import cost structures for green hydrogen with the supplier countries' SGI scoring.

As the empirical analysis suggests, there are significant differences between the 113 assessed countries as per their overall index ranking, but also the individual dimensions composing the index. This allows conclusions to be drawn on the policy focus of potential partnerships and enables policymakers to take choices when facing trade-offs regarding individual dimensions, and to prioritize among the latter.

This paper proceeds as follows. In section 2 we briefly explain the methodology. Section 3 presents the index and the resulting SGI country rankings. In section 4, we discuss the findings, also with a view to specific dimensions making up the index. We in addition juxtapose import costs with the sustainability and governance performance of the assessed countries. Section 5 concludes and offers some policy implications.

2. Method

To construct the index, we followed a four-step process: selecting pertinent dimensions for the index and determining the sample of investigated countries; processing pertinent indicators for these dimensions; managing missing data points; and performing exploratory factorial analysis (EFA). EFA is a vital component of our methodology. The method determines the number of factors emerging from a set of variables and assesses the strength associated with each variable. Put differently, it assesses the correlations between variables, identifying those that vary jointly. This process results in different items forming factors, which, if proposed on a theoretical basis, should allow them to be associated with a particular construct. This construct is then interpreted and defined by the researcher, providing valuable insights into the underlying patterns and interrelationships among variables in the index construction. Utilizing spreadsheets and SPSS Statistics 28 software, we implemented these four steps to ensure a comprehensive and rigorous approach to index construction.

We initially identified five pertinent dimensions for judging the suitability of partner countries in green hydrogen partnerships: (1) Political will: does a given country aim to establish a green hydrogen economy?; (2) Transaction costs: does a given country already have existing trade relations with Europe, and Germany?; (3) Climate ambition: does a given country commit to multilateral climate agreements and climate goals?; (4) Sustainability in regulation: is a given country's regulatory environment susceptible to ensuring and promoting sustainability in green hydrogen production?; and (5) Good governance: does a given country follow the rule of law and is it politically stable? Dimensions 1 and 2 indicate the political commitment to scale up hydrogen exports in a timely manner. By contrast, dimensions 3 through 5 were informed by the policy imperative to ensure environmental and political costs are central pillars of prospective green hydrogen partnerships.

The five dimensions resulted from a two-day exploratory research workshop organized at the Willy Brandt School of Public Policy at the University of Erfurt, as part of a semester-long capstone project on 'Prospects for green hydrogen. How climate diplomacy can support German and global energy transitions'. The workshop took place in December 2020 and brought together ten graduate students with diverse professional and academic backgrounds, representing a cross-section of geographical regions, including Latin America, Africa, East Asia as well as North America. All participants studied for their Master of Public Policy, a professional graduate program for early to mid-career professionals, and had attended energy policy trainings as part of their graduate course. Organized around the broad themes of politics, economics, environment and regulation, workshop participants identified a set of pertinent aspects for judging sustainability and regulatory prowess, extracted from an in-depth literature review preceding the workshop.

The discussion was also informed by pertinent policy studies, including the 2019 IRENA report on hydrogen (IRENA 2019) as well as governmental policy priorities defined by importers, notably in the shape of the German National Hydrogen Strategy (BMWK 2023). Identified aspects included existing trade or energy partnership with Germany or Europe, investment security, renewable energy regulation, government support for H2 projects, H2 pilot or commercial projects, strong domestic institutions or the level of climate ambition. A subsequent feedback round with experts from the capstone client, a European energy and climate policy consultancy, resulted in a classification of the identified criteria under the above mentioned five rubrics or 'dimensions'.

Drawing on the capstone results and additional research, we selected specific indicators for each dimension based on Al Waer and Sibley's (2005) framework to ensure ease of understanding, reliability, and data accessibility. Here we followed MacCallum *et al* (1999) in that we ensured that the selected indicator correspond to the assessed construct, and address the various components contributing to the examined dimension. As a consequence, each dimension was assigned at least two indicators. Data for each indicator were collected for all countries, and by their most recent availability, and data collection was finalized in January 2023. A total of

Table 1. Refined dimensions and indicators.

Governing Performance and International Climate Engagement	Political Will for Hydrogen	Energy Policy Alignment with Germany and the EU
• Fragile states index • Political stability and absence of Violence/Terrorism • Regulatory quality • Rule of law • Corruption perception index • Government effectiveness • Trade freedom index • Energy trilemma index • Environmental performance index • Powering past coal alliance	• Hydrogen pilot programs • Green hydrogen pilot programs • Active pilot programs • Hydrogen strategies	• Energy partnerships with Germany • Incentives and regulatory support for renewable energy • Carbon pricing and GHG emissions monitoring • Legal framework for renewable energy • Energy partnerships with EU

Source: authors' own elaboration.

19 suitable indicators for the chosen five dimensions provided data for a total of 113 countries.

Our chosen statistical method for constructing the index was EFA. EFA resulted in refining the initially identified five dimensions into three characterized by high-communality indicators. These were identified as Governing Performance and International Climate Engagement, Political Will for Hydrogen, and Energy Policy Alignment with Germany and the EU. Table 1 summarizes the refined dimensions and indicators. For additional details on the methodology see the supplementary material.

3. Results

Figure 1 presents the results of the SGI ranking individual countries. The darker the shade of a given country on the map, the higher its position is on the SGI ranking. Conversely, lighter shaded countries are ranked lower in terms of sustainability and governance and the extent to which countries may be suitable for green hydrogen partnerships. As per our methodology, countries shaded gray are not part of our sample. For the former, the numerical results as well as the scores for each dimension see the supplementary material.

The countries in the top ten positions are Australia, the United States, the United Kingdom, Japan, Canada, China, Norway, Chile, India, and Switzerland. Bosnia and Herzegovina, Philippines, Panama, Botswana, Sri Lanka, Jamaica, Kenya, Vietnam, Kuwait, Senegal, and the Dominican Republic populate the middle-ground, that is in the ranks of from 50 to 60. The low-performing countries in the bottom ten slots of the SGI are Sierra Leone, Myanmar, Sudan, the Democratic Republic of the Congo, Venezuela, Republic of the Congo, Haiti, Guinea, Burundi, Eritrea, and Turkmenistan.

When considering standard metrics of economic performance and standards of living, such as GDP or the UN's Human Development Index (HDI), which indicate economic and human development or good governance, these rankings are not surprising. Many Global North countries, such as Australia, the United States, the United Kingdom, Japan, Canada, Norway, and Switzerland, rank high in both reference cases (GDP and HDI) for the most updated data in each case (2022 and 2020 respectively). And yet, although the results are in line with popular conceptions for economic strength, some countries such as China, Chile, and India out-perform the expectations from these metrics in the SGI. To be sure, China's high performance on the SGI is not surprising considering its GDP position (position 2 out of 195 (WB 2022)), but it is surprising when one considers its HDI ranking (79th out of 191 (UNDP 2023)). India's situation is similar to China's in that it ranks 5th in GDP (WB 2022) but 130th in HDI (UNDP 2023), and 9th in the SGI. Chile, on the other hand, holds a middle to high ranking in both references, ranking 46th in GDP (WB 2022) and 43rd in HDI (UNDP 2023), but reached the eighth position in SGI.

Importantly, countries with similar rankings on the overall SGI reveal some striking differences when it comes to individual dimensions. Chile, for example, a top-10 performer, ranks 10th in the Governance and International Climate Engagement dimension, but has the highest scores in four indicators within this dimension: Trade Freedom Index, Energy Trilemma Index, Environmental Performance Index, and Government Effectiveness. Chile also ranks second only to Norway (8th on the SGI) in four other indicators: Political Stability, Rule of Law, Fragile States Index and the Corruption Perception Index. Compared to other top 10 performers, India and China underperform regarding environmental performance, political stability, regulatory quality, Fragile States Index, and the Corruption Perception Index.

The dimension of Political Will for Hydrogen is characterized by the most pronounced differences between the top performers and the remaining countries on the SGI. All countries in the top 10 positions, with the exception of Switzerland and the United

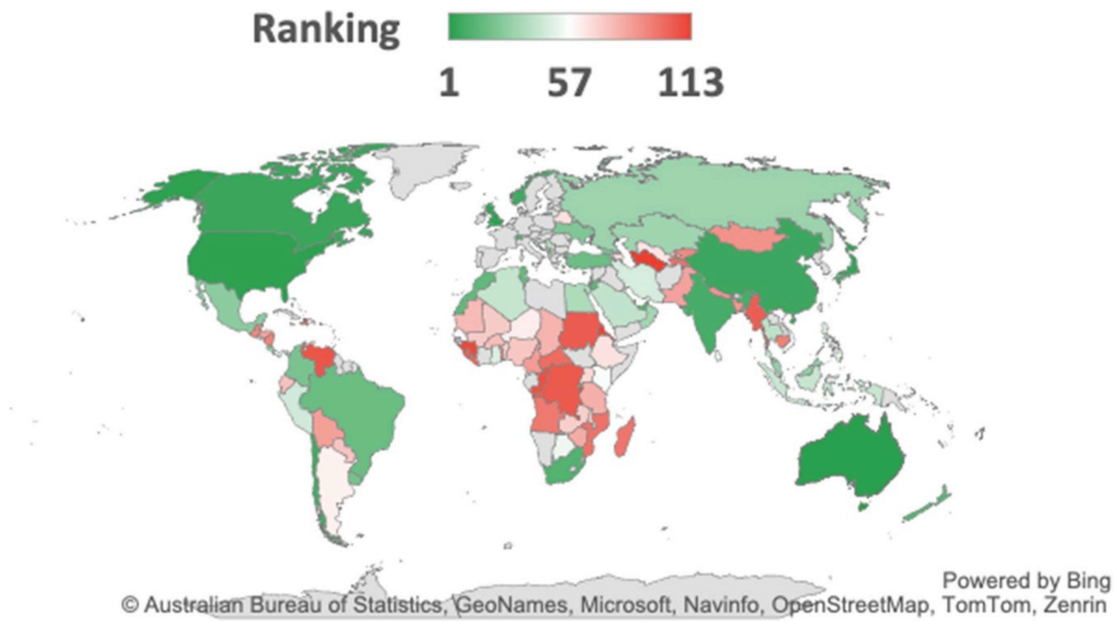

Figure 1. Sustainable and governance index (SGI) for Green Hydrogen.
Source: authors' own elaboration.

States, have a score of 2 in the Hydrogen Strategies indicator[4]. All countries in the lowest 10 positions score 0, i.e. they have neither a hydrogen strategy nor a draft in place, as do all countries in positions 34–60. Overall, a total of 90 countries score 0 in this indicator. Similarly for the indicators Hydrogen Pilot Programs, Active Pilot Programs, and Green Hydrogen Pilot Programs, where all countries in positions 50–60 (excluding Vietnam) and 103–113 score 0, as does an overall total of 74 countries. By contrast, the top 10 ranked countries in the SGI score 2 or more, with Australia and the United States leading in Hydrogen Pilot Programs, the United States and Japan in Active Pilot Programs, and Australia and China in the Green Hydrogen Pilot Programs.

Finally, as regards the dimension of Energy Policy Alignment with Germany and the EU, all countries among the bottom 10 lack systems for carbon pricing and GHG emissions monitoring, whereas several of the top 10 countries have the highest scores for these two indicators. There are significant differences between the highest and the lowest performers for the indicator of Energy Partnerships with Germany, whereas a smaller difference exists in Energy Partnerships with the EU. Here, only four countries (United States, Japan, Canada, and Norway) of the top 10 SGI performers have the highest possible score of 2, whereas the rest of the countries in this group oscillate between the score of 1 and 0. As for Incentives and Regulatory Support for Renewable Energy, the scores in the top 10 ranking countries and the lowest 10 ranking countries are more homogeneous among their respective groups of high, middle, and low performers. Finally, the scores of the top 10 ranked countries in the SGI are high for Legal Framework for Renewable Energy, with most of them scoring 100 except for Japan (score of 80), the United States (60), and Canada (60). Interestingly, there is a significant variance among the bottom 10 countries on the SGI. While Sudan and the Democratic Republic of the Congo score up to 80, Venezuela, the Republic of Congo, and Haiti score 60, compared to Myanmar, Guinea, Burundi, and Eritrea (20) and Turkmenistan (0).

4. Discussion

The SGI allows a clear and aggregated assessment of a given country's relative performance in the dimensions of sustainability and governance with a view to building hydrogen trade partnerships. In that, the SGI score can assist the decision-making process by clarifying a partner country's positioning along the lines of the pertinent dimensions comprising the index. For countries pursuing a proactive, outward-oriented hydrogen strategy, such as Germany, the SGI can indeed provide tangible guidance by vetting targeted partner countries in terms of sustainability and governance. It can also help identify new candidates for the development of ties in hydrogen trade. Here, the general takeaway from the SGI is that a variety of partners with high sustainability and governance performance exist in locations that are comparable regarding pipeline and in shipping distances. That

[4] The United States published their national hydrogen strategy after the data collection was finalized.

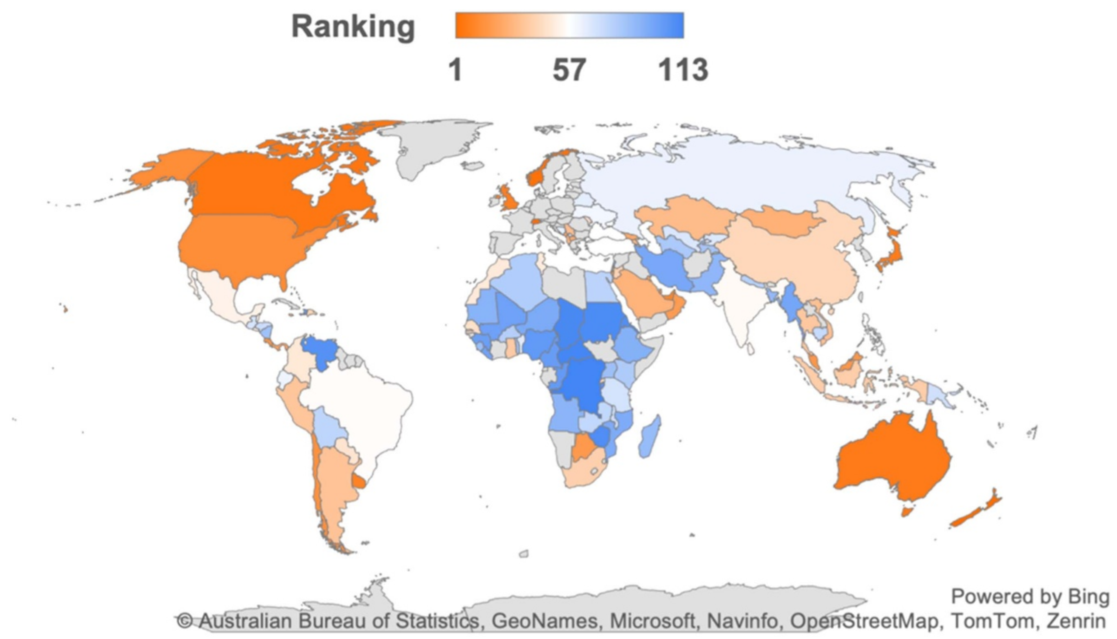

Figure 2. Governing performance and international climate engagement.
Source: authors' own elaboration.

said, it is important to note that the obtained results do not represent an 'ideal' or a 'worst' score, given that the SGI is a composite measure of a country's strengths and weaknesses. As the above results show, countries ranked very similarly may differ considerably when it comes to individual dimensions.

Another analytical added value for policymakers lies in unpacking the performance of all or a specific group of countries with a view to distinct dimensions of interest. Disaggregating the SGI into individual components not only aids the comparison of country rankings across dimensions and against their overall SGI scores. It also caters to the policy preferences of given target audiences and the value they assign to different aspects of the SGI. For the purpose of illustrating this point, figures 2–4 provide a ranking solely focused on one dimension each.

Taking the dimension of Governing Performance and International Climate Engagement (figure 4) as an example, the results generally fall in line with countries' overall SGI rankings. Yet, some countries changed position significantly. Uruguay, for example, is ranked 9th but scores 21 on the SGI. New Zealand even jumps from position 14 (SGI) to the top ranking in this dimension. Other countries, by contrast, score lower. South Africa, for example, ends up on position 39 (12 in the SGI), and Morocco even drops 33 positions compared to its SGI ranking of 16. Clearly, however, assessing partners based on a single dimension risks lopsided decision making.

Another insight from the SGI relates to the extent to which current partnership strategies by importing countries align with the SGI. A case in point is Namibia, a country rich in renewable energy resources and with which Germany concluded a Hydrogen Partnership in 2022: the partnership is underpinned by EUR 40 million in German public funding to explore green hydrogen potential and export possibilities to Germany (BMBF 2021), which are estimated to be worth some USD 10 billion in investment until the end of the decade (Euractive 2023). Yet Namibia was excluded from the SGI sample—as were other countries—as per our methodology, because of a lack of data on key indicators. Uruguay, by contrast, scores 21 on the SGI, has an H2 strategy and is actively engaged in developing a hydrogen economy. So far, however, Germany has not taken determined steps to develop an energy partnership with the country. Therefore, the German strategy raises the question of whether and to what extent there exists an ex-ante assessment of the sustainability and governance aspects pertaining to their emerging partnerships. The more general point here is that patchy or incomplete data patterns on key aspects making up the SGI may point to broader deficiencies in quality infrastructure, (environmental) regulation and institutional capacity in a prospective partner country. This means investing political and financial capital into hydrogen partnerships may come at the risk of the partner country falling short on aspects that are key for establishing and sustaining hydrogen production and exports.

Moreover, the SGI also vividly illustrates the trade-off that may exist between governance and sustainability aspects and costs. In 2023, Germany signed a memorandum of understanding with Egypt on intensifying cooperation in green hydrogen and also fostered ties on green hydrogen as part of the

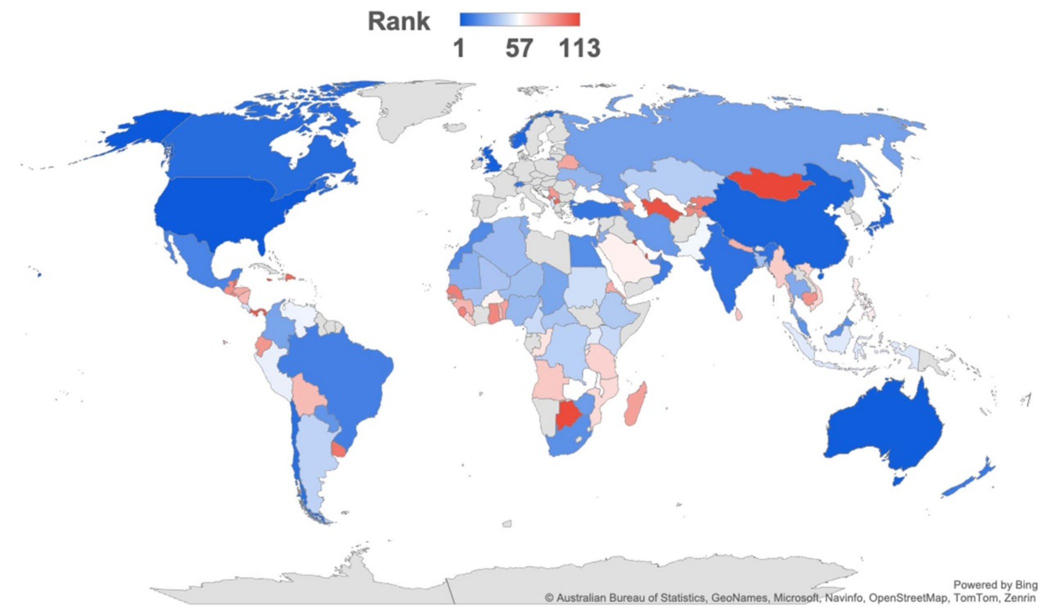

Figure 3. Political will for hydrogen.
Source: authors' own elaboration.

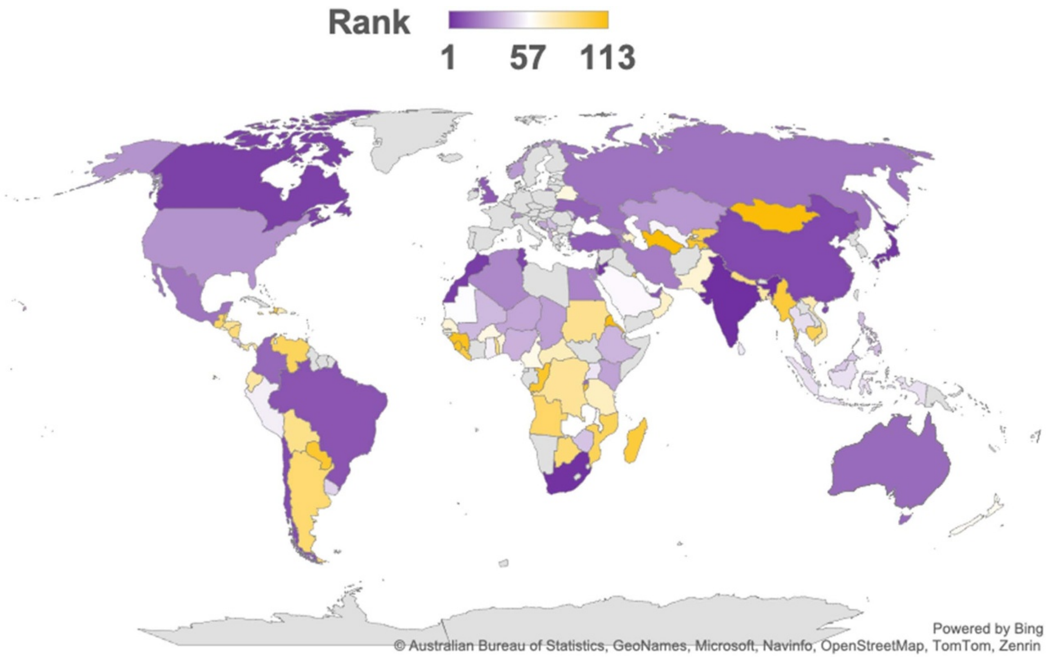

Figure 4. Energy Policy Alignment with Germany and the EU.
Source: authors' own elaboration.

German-Angolan Energy Partnership in 2022. By some estimates, Egypt may be able to produce green hydrogen at 2.25–2.50 EUR/ kg in 2030, whereas Angola could do this at 2.50–2.75 EUR/kg at that time (PWC 2023). This puts both countries on par with Canada or Norway in terms of cost structures. Clearly, it is primarily because of their potential for green hydrogen production at competitive costs that Egypt or Angola are courted by Germany. Yet, whilst Canada ranks first and Norway seventh on the SGI, Egypt ranks at a medium 37th and Angola at a very low 95th spot, raising questions not only regarding sustainability aspects but also the investment environment for green hydrogen projects. Were the SGI to inform country choices, Egypt may be a preferred partner still, whereas Angola arguably would not qualify as such.

To be sure, single initiatives such as the German-Angolan Energy Partnership will not result in the cluster risk of gas sourced from Russia, which was the preferred source due to its affordability and eventually accounted for over 50% of Germany's total imports prior to the Russian invasion of Ukraine in 2022 (Bundesnetzagentur 2023). Yet, as the Ukraine war demonstrates, it is imperative for import dependent countries to build energy trade partnerships that are characterized by stability, reliability, and accountability.

5. Conclusion and policy implications

As green hydrogen emerges as an energy carrier of growing importance for Germany and Europe, the question arises of which countries Germany and Europe would want to partner up with in their external trade relations. Germany alone is pursuing hydrogen-related activities in more than 40 countries outside of the EU, with a view to building sustainable trade relations, involving a total of four main federal ministries (Nunez and Quitzow 2023). As Russia's invasion of Ukraine and the ensuing energy crisis demonstrated, costs alone should no longer drive the choice of external resource suppliers. Import options need to be weighed against their potential political costs, and the security risks associated with lopsided dependency structures. Furthermore, the climate crisis makes sustainability a crucial factor in determining partnerships with external suppliers.

The 113 countries assessed in this paper exhibit significant differences in SGI performance. The empirical evidence also suggests that there are significant differences among similarly ranked countries when it comes to individual dimensions making up the index. This may help in identifying the degree to which green hydrogen partnerships need to prioritize specific aspects covered by the SGI. In that respect, the SGI represents a valuable tool for informing external strategies for green hydrogen trade.

Clearly, the SGI has limitations, an important one of which is the availability of data. This is due to limited access to databases, the samples covered by a given database or the extent to which they are updated and maintained. A second aspect is bias, as it is a relatively small group of organizations that develops and publishes data on sustainability and governance. Moreover, pertinent databases are mostly created by organizations in developed countries, which may imply a lopsided focus when it comes to data collection and organization. Adding to this, available data to some extent determine the chosen measures. For example, hydrogen pilot programs were assessed solely based on their existence, without taking into consideration volume or capacity. Future research could enhance the empirical basis here and add further granularity to the empirical investigation. This could also include additional aspects so far not considered in the index, for example the extent to which hydrogen strategies consider supply chain emissions (White et al 2021). Moreover, the chosen quantitative approach can only capture in-country dynamics to a limited degree. Country case studies are needed to add further granularity in terms of data and contextualize the quantitative results. This calls for qualitative research, and the imperative to complement the present study with primary data analysis. Finally, the SGI and the dimensions it captures do not allow any statements on whether a given country may or may not emerge as a viable exporter. This, by contrast, will depend on domestic policy choices. A case in point is Japan, which scores high on the SGI but does not have plans to export green hydrogen at this moment in time.

That said, the SGI is an important complement to incumbent criteria informing green hydrogen partnerships, notably factors determining their economic viability. Geography, for example, may affect transport costs but also has implications for transport infrastructure. As studies suggest, for high-volume hydrogen transport, it is pipelines that provide the most cost-effective solution. If liquified or converted into a synthesis product such as ammonia or a liquid organic hydrogen carrier (LOHC), hydrogen transport by some estimates increases costs by 25% compared to pipelines (Wietschel et al 2022). For the EU, this limits the potential pool of partner countries to states in Northern Africa, Norway, Ukraine, and potentially the Middle East (Wang et al 2021). A combined assessment building on production costs, geography, and the SGI may facilitate the identification of win-sets, where countries that score high on the SGI are located in geographic proximity and promise low production costs. For example, Morocco features one of the lowest export costs for hydrogen, estimated at €3.72/KgH2 for a German delivery point (Aurora 2023). The country is ranked 16th on the SGI, lies close to the EU, and is already linked to the European energy market through existing gas pipeline infrastructure.

Clearly, as the green hydrogen sector is currently only in its infancy and will see steep technology learning curves, there is reason to assume that long-distance hydrogen transport will eventually prove cost effective thanks to falling production costs and the diversified use of P2X. This may level the playing field to some extent and make top SGI-performing countries such as Australia or Canada interesting green hydrogen partners for Germany and Europe.

Still, and such win-sets disregarding, the present analysis suggests that there exist trade-offs between low export costs, geography, and sustainability and (good) governance. Some countries may score high on the SGI but be burdened by production and export costs that are uneconomical. This implies that Europe and Germany may need to take clear choices between normative, that is climate-related, and economic targets. Achieving both at the same time may be a tough call.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The Authors declare no Competing Financial or Non-Financial Interests.

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References

Al Waer H and Sibley M 2005 Building sustainability assessment methods: indicators, applications, limitations and development trends *Conf. on Sustainable Buiding South East Asia, Kuala Lumpur, Malaysia* pp 1–13 (available at: www.irbnet.de/daten/iconda/CIB_DC23506.pdf) (*Accessed 21 September 2023*)

Aurora 2023 Renewable hydrogen imports could compete with eu production by 2030 (available at: https://auroraer.com/media/renewable-hydrogen-imports-could-compete-with-eu-production-by-2030/) (Accessed 21 September 2023)

Bhagwat S and Olczak M 2020 *Green Hydrogen. Bridging the Energy Transition in Africa and Europe* (EUI Florence School of Regulation) (available at: 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 21 September 2023)

BMBF 2021 Karliczek: germany and Namibia form partnership for green hydrogen (available at: www.bmbf.de/bmbf/shareddocs/pressemitteilungen/de/2021/08/172_namibia_eng.pdf?__blob=publicationFile&v=1) (Accessed 21 September 2023)

BMWi 2020 Energy partnerships and energy dialogues (available at: www.bmwk.de/Redaktion/EN/Publikationen/Europe/energy-partnerships-and-energy-dialogues-2020.pdf?__blob=publicationFile&v=6) (Accessed 30 September 2023)

BMWK 2020a The national hydrogen strategy (available at: www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html) (Accessed 21 September 2023)

BMWK 2020b 'Haru Oni' PtX project Minister Altmaier hands over first approval notice for international green hydrogen project (available at: www.bmwk.de/Redaktion/EN/Pressemitteilungen/2020/12/20201202-haru-oni-ptx-project-minister-altmaier-hands-over-first-approval-notice-for-international-green-hydrogen-project.html) (Accessed 21 September 2023)

BMWK 2021 Declaration of Intent signed to establish German-Australian hydrogen alliance (available at: www.bmwk.de/Redaktion/EN/Pressemitteilungen/2021/06/20210613-declaration-of-intent-signed-to-establish-german-australian-hydrogen-alliance.html) (Accessed 21 September 2023)

BMWK 2022 Klima, Energie und Wasserstoffpartnerschaften (available at: www.bmwk.de/Redaktion/DE/Artikel/Energie/internationale-energiepolitik-2.html) (Accessed 21 September 2023)

BMWK 2023 *National Hydrogen Strategy Update* (Federal Ministry for Economic Affairs and Climate Action)

Böhringer C and Jochem P E 2007 Measuring the immeasurable—A survey of sustainability indices *Ecol. Econ.* **63** 1–8

Brändle G, Schönfisch M and Schulte S 2021 Estimating long-term global supply costs for low-carbon hydrogen *Appl. Energy* **302** 117481

Bundesnetzagentur 2023 Bundesnetzagentur publishes gas supply figures for 2022 (available at: www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/EN/2023/20230105_RueckblickGas2022.html) (Accessed 21 September 2023)

Bundesregierung 2023 Internationale Wasserstoffzusammenarbeit (available at: www.bmwk.de/Navigation/DE/Wasserstoff/Internationale-Wasserstoffzusammenarbeit/internationale-wasserstoffzusammenarbeit.html) (Accessed 30 September 2023)

Caro K 2021 Measuring digital citizenship. A quantitative approach to understand its relevance and dimensions in a global context *Thesis submitted in partial fulfilment of the requirements for the degree of Master of Public Policy 2021* Willy Brandt School of Public Policy University of Erfurt

DeCoster J and Claypool H 2004 Data analysis in SPSS (available at: www.stat-help.com/notes.html) (Accessed 15 May 2021)

Dietz C and Vacha V 2021 Germany: the German National Hydrogen Strategy and international hydrogen partnerships (available at: www.globalcompliancenews.com/2021/10/18/germany-the-german-national-hydrogen-strategy-and-international-hydrogen-partnerships-06102021/) (Accessed 21 September 2023)

Euractiv 2023 Namibia moves ahead on green hydrogen project with German investors (available at: www.euractiv.com/section/energy-environment/news/namibia-moves-ahead-on-green-hydrogen-project-with-german-investors/) (Accessed 21 September 2023)

European Commision 2022a Communication from the commission to the european parliament, the european council, the council, the european economic and social committee and the committee of the regions *REPowerEU Plan* (Brussels) (available at: www.reteambiente.it/repository/normativa/48230_comunicazione18_maggio_2022repowereu.pdf) (Accessed 21 September 2023)

European Commission 2020 A hydrogen strategy for a climate-neutral Europe. Communication from the commission to the European parliament, the council, the European economic and social commitee and the committee of the regions (COM/2020/301) (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0301) (Accessed 21 September 2023)

European Commission 2022b Implementing the REPowerEU action plan: investment needs, hydrogen accelerator and achieving the bio-methane targets. Accompanying the document. Communication from the Commission to the European Parliament *The European Council, the Council, the European Economic and Social Committee and the Committee of the Regions* (REPowerEU Plan." Brussels (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022SC0230) (Accessed 21 September 2023)

European Commission 2022c European partnerships in climate, energy and mobility (available at: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/european-partnerships-horizon-europe/climate-energy-and-mobility_en) (Accessed 21 September 2023)
European Commission 2022d REPowerEU: joint European action for more affordable, secure and sustainable energy *Fact Sheet* (available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_1511) (Accessed 21 September 2023)
European Commission 2023 Key partner countries and regions (available at: https://energy.ec.europa.eu/topics/international-cooperation/key-partner-countries-and-regions_en) (Accessed 21 September 2023)
Fabrigar L R and Wegener D T 2011 *Exploratory Factor Analysis* (Oxford University Press)
Fein E C, Gilmour J, Machin T and Hendry L 2022 *Statistics for Research Students. An Open Access Resource with Self-Tests and Illustrative Examples* (University of Queensland)
Fund for Peace 2023a Indicators (available at: https://fragilestatesindex.org/) (Accessed 21 September 2023)
Fund for Peace 2023b Methodology (available at: https://fragilestatesindex.org/methodology/) (Accessed 21 September 2023)
Goldthau A and Sitter N 2022 Whither the liberal European Union energy model? The public policy consequences of russia's weaponization of energy *EconPolForum* **23** 4–7 (available at: https://www.cesifo.org/DocDL/econpol-forum-2022-6-goldthau-sitter-eu-energy-model.pdf
Heinemann C, Mendelevitch R, Herold A, Jakob M, Kampffmeyer N, Kasten P and Seebach D 2021 Sustainability dimensions of imported hydrogen *(No. 8). Working Paper* (Oeko-Institut) (available at: www.oeko.de/fileadmin/oekodoc/WP-imported-hydrogen.pdf) (Accessed 21 September 2023)
Holgado–Tello F P, Chacón–Moscoso S, Barbero–García I and Vila–Abad E 2010 Polychoric versus Pearson correlations in exploratory and confirmatory factor analysis of ordinal variables *Qual. Quantity* **44** 153–66
Hydrogen Council 2020 Path to hydrogen competitiveness (available at: https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf) (Accessed 21 September 2023)
Hydrogeninsight 2023 Norway and Germany announce plan to build hydrogen pipeline between the two countries by 2030 (available at: www.hydrogeninsight.com/policy/norway-and-germany-announce-plan-to-build-hydrogen-pipeline-between-the-two-countries-by-2030/2-1-1383658?utm_source=email_campaign&utm_medium=email&utm_campaign=2023-01-05&utm_term=recharge&utm_content=hydrogen) (Accessed 21 September 2023)
International Energy Agency 2021 Hydrogen production and infrastructure projects database (available at: www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database#hydrogen-production-projects) (Accessed 21 September 2023)
IRENA 2019 *Hydrogen: A Renewable Energy Perspective* (International Renewable Energy Agency)
Lenivova V 2022 Potential development of renewable hydrogen imports to European markets until 2030 (Oxford Institute for Energy Studies) (available at: www.oxfordenergy.org/wpcms/wp-content/uploads/2022/03/Potential-development-of-renewable-hydrogen-imports-to-European-markets-until-2030-ET08.pdf) (Accessed 21 September 2023)
MacCallum R C, Widaman K F, Zhang S and Hong S 1999 Sample size in factor analysis *Psychol. Methods* **4** 84
NASA Socioeconomic Data and Applications Center 2020 Environmental performance index (available at: https://sedac.ciesin.columbia.edu/data/set/epi-environmental-performance-index-2020) (Accessed 21 September 2023)
Nunez A and Quitzow R 2023 Germany's hydrogen strategy: securing industrial leadership in a carbon-neutral economy (Research Institute for Sustainability) (available at: https://publications.rifs-potsdam.de/rest/items/item_6002778_3/component/file_6002779/content) (Accessed 21 September 2023)
PPCA 2023 Our story (available at: https://poweringpastcoal.org/our-story/#/) (Accessed 21 September 2023)
PWC 2023 The green hydrogen economy (available at: www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html) (Accessed 21 September 2023)
Qualtrics 2023 What is factor analysis and how does it simplify research findings? (available at: www.qualtrics.com/experience-management/research/factor-analysis/) (Accessed 21 September 2023)
RISE 2023a About us (available at: https://rise.esmap.org/about-us) (Accessed 21 September 2023)
RISE 2023b Carbon pricing and monitoring (available at: https://rise.esmap.org/indicators (Accessed 21 September 2023)
RISE 2023c Incentives and regulatory support for renewable energy (available at: https://rise.esmap.org/indicators) (Accessed 21 September 2023)
RISE 2023d Legal framework for renewable energy (available at: https://rise.esmap.org/indicators) (Accessed 21 September 2023)
The Global Economy 2023a About the Site (available at: www.theglobaleconomy.com/) (Accessed 21 September 2023)
The Global Economy 2023b List of available indicators (available at: www.theglobaleconomy.com/indicators_list.php) (Accessed 21 September 2023)
Transparency International 2021 Corruption perceptions index (available at: www.transparency.org/en/cpi/2021) (Accessed 21 September 2023)
UNDP 2023 Human development index (available at: https://hdr.undp.org/data-center/human-development-index#/indicies/HDI) (Accessed 21 September 2023)
Wang A, Jens J, Mavins D, Moultak M, Schimmel M and van der Leun K 2021 European Hydrogen Backbone. Analysing future demand, supply, and transport of hydrogen (Creos, DESFA, Elering, Enagás, Energinet) (available at: https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supplyand-transport-of-hydrogen_June-2021_v3.pdf) (Accessed 21 September 2023)
WB 2022 Gross domestic product 2022 (available at: https://databankfiles.worldbank.org/public/ddpext_download/GDP.pdf) (Accessed 21 September 2023)
WB 2023a Government effectiveness (available at: http://info.worldbank.org/governance/wgi/Home/downLoadFile?fileName=ge.pdf) (Accessed 21 September 2023)
WB 2023b Metadata glossary (available at: https://databank.worldbank.org/metadataglossary/world-development-indicators/series/NY.GDP.MKTP.KD.ZG~:~:text=GDP%20is%20the%20sum%20of,Source) (Accessed 21 September 2023)
WB 2023c Political stability and absence of terrorism (available at: http://info.worldbank.org/governance/wgi/Home/downLoadFile?fileName=pv.pdf) (Accessed 21 September 2023)
WB 2023d Regulatory quality (available at: http://info.worldbank.org/governance/wgi/Home/downLoadFile?fileName=rq.pdf) (Accessed 21 September 2023)
WB 2023e Rule of law (available at: http://info.worldbank.org/governance/wgi/Home/downLoadFile?fileName=rl.pdf), (Accessed 21 September 2023)
WB 2023f Worldwide governance indicators (available at: http://info.worldbank.org/governance/wgi/Home/Documents), (Accessed 21 September 2023)
Wendling Z A, Emerson J W, de Sherbinin A and Esty D C 2020 2020 environmental performance index (Yale Center for

Environmental Law & Policy) (available at: epi.yale.edu) (Accessed 21 September 2023)
White L V, Fazeli R, Cheng W, Aisbett E, Beck F J, Baldwin K G H, Howarth P and O'Neill L 2021 Towards emissions certification systems for international trade in hydrogen: the policy challenge of defining boundaries for emissions accounting *Energy* **215** 119139
Wietschel M *et al* 2022 War in Ukraine: implications for the European and German strategies for importing hydrogen and synthesis products (available at: www.hypat.de/hypat-wAssets/docs/publications/2022/2022-03-21_HyPAT_Impulspapier_Ukraine-english.pdf) (Accessed 21 September 2023)
World Energy Council 2023 Energy trilemma index (available at: https://trilemma.worldenergy.org/#!/energy-index), (Accessed 21 September 2023)
Yong A G and Pearce S 2013 A beginner's guide to factor analysis: focusing on exploratory factor analysis *Tutorials Quant. Methods Psychol.* **9** 79–94