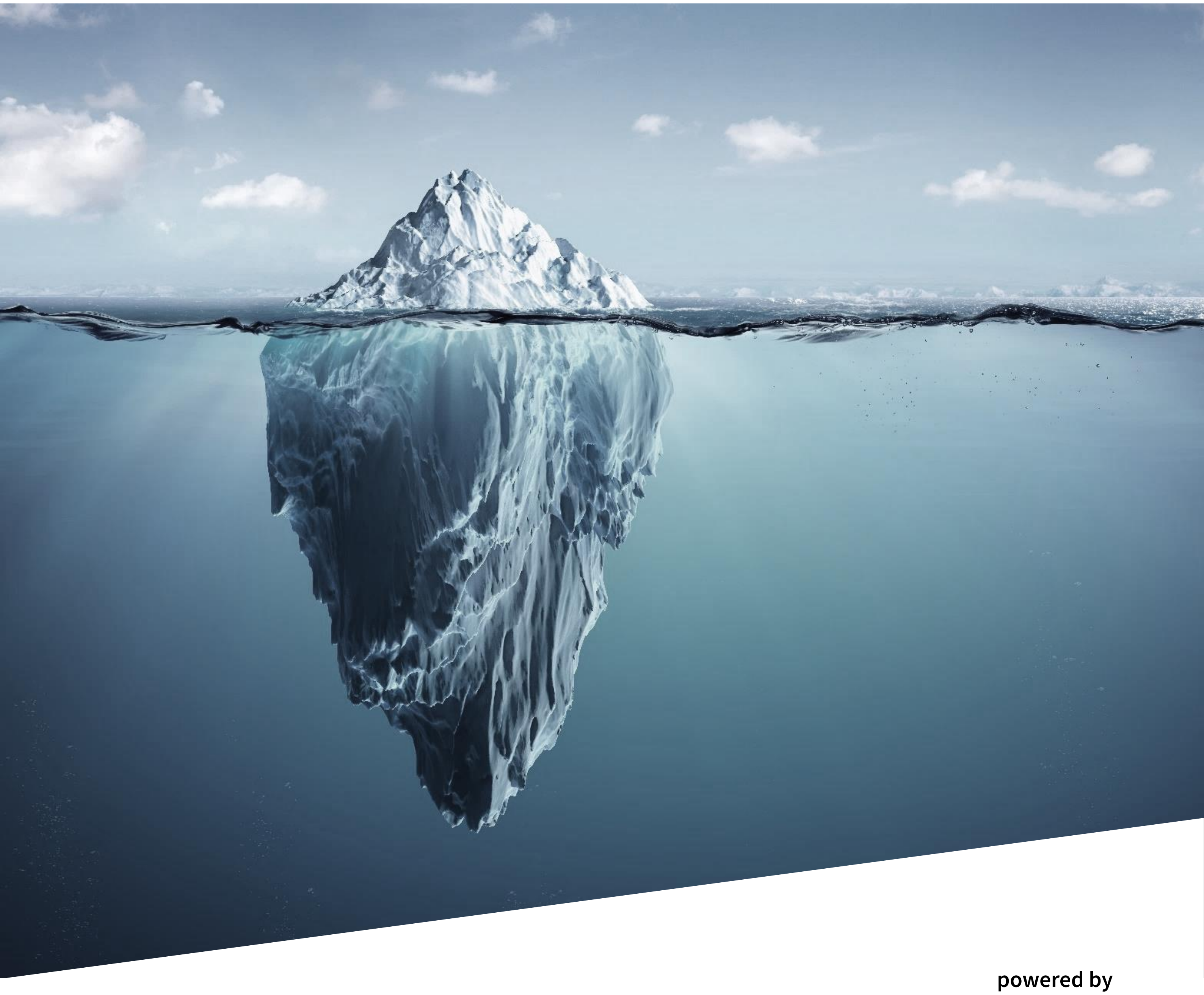
Global Alliance POWERFUELS

Renewable Hydrogen Project Risks

Categorising, assessing and mitigating risks along the hydrogen value chain



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Content

Key Results

Main Takeaways

- The overall risk of implementing large-scale green hydrogen projects is generally higher in many export-oriented, potentially pipeline-connected countries outside of the EU than for projects in the EU / EFTA.
- When ranking risks by likelihood and severity, financing risks, supply chain-related risks and reputational risks are most critical for the success of large-scale projects located in the EU / EFTA, whereas governmental risk is most important for projects in countries outside the EU.
- Mitigation options mostly need to be tailored individually, as there are currently no "off-the-shelf" hydrogen projects.
- The development of mitigation options is expected to follow the development of the hydrogen market, similar to the development of mitigation options for renewable energy projects in more mature markets.

Mitigating renewable hydrogen project risks: a key factor in ramping up the market

While the importance of renewable hydrogen and its derivatives for reaching climate neutrality and increasing energy security is widely recognised, enabling viable investment opportunities in the nascent hydrogen industry remains challenging. A focus on risk mitigation is needed to accelerate hydrogen production and deployment and activate private capital. Identifying, assessing and prioritising risks forms the very basis of risk management in green hydrogen projects. Five categories of risks have been identified: Project development and technology risks, political risks, economic risks, midstream risks and environmental risks. To develop a tailored mitigation strategy, projects developers should assess and rank the determined risks by their likelihood and severity, i.e., the expected harm if they materialise.

Europe will rely on large hydrogen projects in non-EU / EFTA countries to meet its demand, but these often have higher risks

To meet the future European demand for green hydrogen, the advancement of projects in the European Union (EU), the European Free Trade Association (EFTA), and imports from outside the EU / EFTA will be required. The risk profiles of prototypical emerging projects targeting the European offtake market vary significantly, with location and scale being important factors in assessing the pertinent risks. Generally, risks are higher overall in many export-oriented, potentially pipeline-connected countries outside of the EU than for projects in the EU / EFTA. In consequence, projects in these locations face high financing costs and strategies to limit or transfer risks are critical to attract investments.

Projects outside EU / EFTA: governmental risk most significant

The generally more unstable political and economic environment in many countries of production considered as possible future exporters of gaseous hydrogen to Europe makes governmental risk the most critical for the success of green hydrogen projects. Within the category of political risks, governmental risk addresses the structural and institutional dimension of governance practices, principles and processes. Strategies to mitigate the associated factors are not always well-known. However, a range of governmental risk mitigation options in the form of instruments and schemes to promote foreign trade and investment already exist. Examples of instruments to mitigate government risk include political risk insurances (PRI) or sovereign guarantees.

Projects in the EU / EFTA face critical but no catastrophic risks

In large-scale projects located in the EU / EFTA, regulatory risk is relatively high compared to other risk categories, as the regulatory framework for renewable hydrogen is still developing. In practice, long-term offtake, which is usually a prerequisite for making renewable hydrogen projects bankable, is difficult to secure under conditions of uncertainty. In addition, the length of approval processes can lead to significant delays in the implementation of projects. Financing risks, supply chain-related risks and reputational risks are also found to be critical for the success of large-scale projects within the EU / EFTA, albeit having a lower likelihood of occurrence.

Small-scale projects in Germany show the lowest absolute risk score of the cases assessed

A third test case examines small-scale projects in Germany. These are characterised by comparatively lower renewable energy potential and potentially higher wage levels. Nevertheless, this case faces the lowest risks overall due to the stable political and economic situation in Germany and the small size of the considered projects in comparison to the other assessed test cases.

Risk acceptance can be a legitimate strategy for risks that are both unlikely and inconsequential

Accepting risks can be a valid and suitable strategy for dealing with identified risks. This is the most appropriate and often the least expensive strategy when the potential risk is unlikely to occur, and its severity is low or negligible. It is important to note that accepting risks does not imply disregarding them.

An effective mitigation strategy, usually involving risk limitation or transfer, is central to making projects economically viable

Implementing practicable, efficient and cost-effective risk mitigation tools and strategies can make a significant contribution to reducing the cost of capital and making projects economically viable. Risk limitation is the most common mitigation strategy. It implies reducing a project's exposure to a specific identified risk and reducing the impact of any possible consequences. Risk transfer, on the other hand, involves passing risks on to a willing third party, such as a contracting partner, bank or insurance company. Public and international institutions can also act as risk-absorbing third parties. Specific examples of risk transfer options for renewable hydrogen projects include contractual provisions (e.g., penalty payments), insurance policies or hedging instruments.

Few "off-the-shelf" mitigation products for green hydrogen projects exist to date

As the hydrogen market is still evolving, so far, no "off-the-shelf" green hydrogen projects exist which require the individualisation of risk mitigation strategies for each project. This need for "tailor-made" solutions currently contributes to the relatively high cost of risk mitigation for green hydrogen projects, given the early stage of the industry. Drawing parallels with the development of risk mitigation solutions in the renewable energy sector, it is anticipated that, as the hydrogen market matures, the costs associated with risk mitigation will decrease over the coming years. This trend will provide greater certainty to developers, and facilitate a more expedient and straightforward implementation of green hydrogen projects.

1 Introduction

Hydrogen projects face risks along the entire value chain, impeding investments

Powerfuels, i.e. "green" hydrogen produced from renewable electricity via water electrolysis and its derivatives, will have an indispensable role in reaching climate neutrality and de-fossilising applications that are difficult to electrify directly. In 2022, in light of Russia's invasion of Ukraine, the EU increased its target for the production of renewable hydrogen in Europe to 10 million tons (mt) by 2030 in its REPowerEU plan, recognising that an accelerated expansion of green hydrogen production capacities can also contribute to diversified energy supplies and independence from Russian fossil fuel imports. If this target is achieved, about 3% of the EU's energy demand could be met by domestic renewable hydrogen by 2030.

However, no liquid market for green hydrogen exists to date and few renewable hydrogen financing deals have been closed. More than 1,400 renewable and low-carbon hydrogen projects representing $570b of investment by the end of 2030 have been announced globally, although less than 7% have reached a final investment decision (FID).[1] This points to the prevailing uncertainty about the regulatory and market framework conditions, and the risk-return profile of projects.

Project risks, as defined in this report, refer to uncertain events or conditions that will have a negative effect on one or more project objectives if they occur. As many renewable hydrogen projects pass the demonstration stage and the focus shifts towards commercialisation and industrialisation, complexity, for example with regard to supply chains, financing, and demand-side structures to secure offtake, increases. Understanding the most relevant risks for different types of projects can help to prioritise them, and to define and develop tailored risk management or mitigation strategies, i.e. instruments that can diversify, hedge or transfer these risks. From a practical perspective, defining standards and best practices from "early mover" projects, and categorising and allocating risks in a way that is familiar to project investors, can contribute to successfully financing green hydrogen projects and advancing the market ramp-up of powerfuels.

While there is a growing body of literature on the requirements of developing a global green hydrogen market, studies on hydrogen project-related risks have predominantly focused on potential safety threats or technical failure[2]. This report takes a broader perspective, identifying and classifying renewable hydrogen project risks along the entire value chain across technical, economic, political and environmental dimensions.

Objective and method

This report identifies the risk factors associated with green hydrogen projects and highlights the central role of risk management strategies. Through an extensive literature review, 52 specific risks are identified, covering the entire value chain of green hydrogen project planning, and categorised into 13 risk clusters. These risks are then applied to three test cases of stylised prototypical green hydrogen projects, which differ in terms of their geographical scope and the size of the associated electrolysers.

The selection of the test cases takes into account numerous factors, including the renewable energy potential of the project region, the final destination or end use of the hydrogen produced, and the prevailing political and macroeconomic environment. To select the test cases, an analysis of announced green hydrogen projects within and outside the EU, with a focus on export to Europe, is undertaken.

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[1] Hydrogen Council, "Hydrogen Insights 2023 – December Update", 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf, accessed January 2024.
[2] Tetiana Hilorme et al., "Formation of Risk Mitigating Strategies for the Implementation of Projects of Energy Saving Technologies", *Academy of Strategic Management Journal* 18, no. 3 (2019), https://www.abacademies.org/articles/formation-of-risk-mitigating-strategies-for-the-implementation-of-projects-of-energy-saving-technologies-8125.html, accessed December 2023.

Various maps and studies are compared, showcasing emerging patterns and clusters in the distribution of renewable hydrogen projects. As a result, these test cases cover a wide range of green hydrogen project scenarios, with a focus on the European context.

Using a Risk Assessment Matrix (RAM), all the risks identified are assessed for each of the three test cases. Specifically, the risks are attributed numerical values for each test case, based on a qualitative literature-informed assessment. A ranking of possible risks is derived from the numerical values, and visualised in RAMs.

The main result of the analysis is that particularly the geographical location, has a significant impact on the risk profile of a green hydrogen project. This underlines the highly project-specific nature of the emerging risks, and highlights the critical importance of taking a tailored risk management approach.

The final part outlines the risk management process and identifies four main categories of risk mitigation strategies: risk acceptance, limitation, transfer and avoidance. Selecting a strategy that is appropriate mainly depends on the severity and likelihood of the respective identified risks. The report lists and contextualises a wide range of mitigation strategies by aligning them with the risk clusters, thus highlighting potential avenues for risk reduction.

Scope of the report

Geographically, the report is limited to electrolytic renewable electricity-based hydrogen used or consumed in the EU, with production taking place either within Europe or in a third country. Only projects for producing gaseous renewable hydrogen in its pure form, i.e. no derivatives such as ammonia or methanol, are considered, confining distances for transporting the hydrogen.

Two types of projects are covered in terms of size: large-scale green hydrogen projects with an electrolyser capacity of at least 20 MW, and small-scale projects with capacities of up to 1 MW. The focus is placed on identifying the risks from the project developer's perspective. Consequently, planning and development, construction, operation and maintenance, and margin/sale are considered to be the stages in which risks may arise.

2 Green Hydrogen Project Risks

Identifying and categorising risks along the hydrogen value chain

The following literature review identifies, defines and categorises the key risks relevant to green hydrogen projects. Although the production of green hydrogen via water electrolysis is not a new technology, its implementation on an industrial scale is only currently developing, with the world's largest operational green hydrogen project to date having an installed capacity of 260 MW.[3] Studies or reports focusing on risk management in hydrogen projects are therefore rare. For this reason, key points from the literature on risk classification and management in other renewable energy projects are examined and transferred to green hydrogen projects where applicable.[4] [5] [6] [7] [8] [9]

The planning, construction and operation of a green hydrogen project is a complex and long-term venture, in which several economic, technical and financial actors are involved along the value chain. In order to comprehensively and accurately map and define single project risks, the prospects of, and consequences for, the following actors are considered:

- Project owners
- Project developers
- Financial institutions and financers

Project risks can occur along the entire value chain of green hydrogen projects. The stylized value chain, depicted in Figure 1 is used to work out and pinpoint single risks.

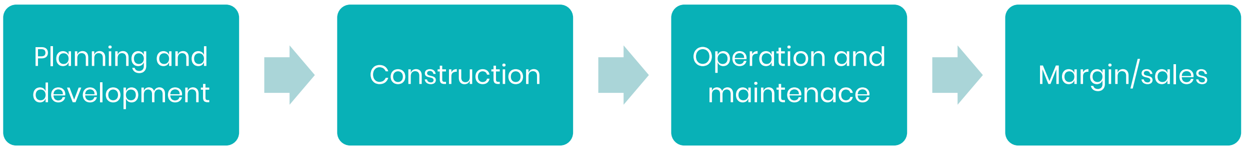

Figure 1: Stylized hydrogen project value chain

3 The world's largest operational green hydrogen project, consisting of 52 PEM electrolysers with a capacity of 5 MW each, is located in Xinjiang, China: Polly Martin, "World's largest green hydrogen project begins production in China", Hydrogen insight powered by Recharge - Global news and intelligence for the Energy Transition, 2023, https://www.hydrogeninsight.com/production/worlds-largest-green-hydrogen-project-begins-production-in-china/2-1-1478233, accessed December 2023.

4 Nadine Gatzert and Thomas Kosub, "Risks and risk management of renewable energy projects: The case of onshore and offshore wind parks", *Renewable and Sustainable Energy Reviews* 60, 2016.

5 "Wasserstoff im Klimaschutz: Klasse statt Masse", Stellungnahme, 2021, https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.pdf?__blob=publicationFile&v=4.

6 Ilan Alon, "A normative model of macro political risk assessment", Multinational Business Review, 1998, https://www.academia.edu/668635/A_normative_model_of_macro_political_risk_assessment.

7 Federal Ministry for Economic Cooperation and Development, "Analysing and managing climate risks", 2022, https://www.bmz.de/en/issues/climate-change-and-development/climate-risk-management, accessed January 2023.

8 "Green energy choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production," 2016.

9 Florian Egli, "Renewable energy investment risk: An investigation of changes over time and the underlying drivers", *Energy Policy* 140, 2020.

Project-related risks occur at several stages of the value chain and usually concern more than one actor.

To classify and group risks that may occur over the course of a project, we establish five risk dimensions (1st tier risks) with 13 more specific risk categories (2nd tier risks), see Figure 2. It is important to note that the analysis of these risk dimensions and categories takes the perspective of project developers and owners into account, hence describing the risks that can impede the successful implementation of green hydrogen projects. Additionally, the risk categories are examined separately, without taking into account their interdependencies.

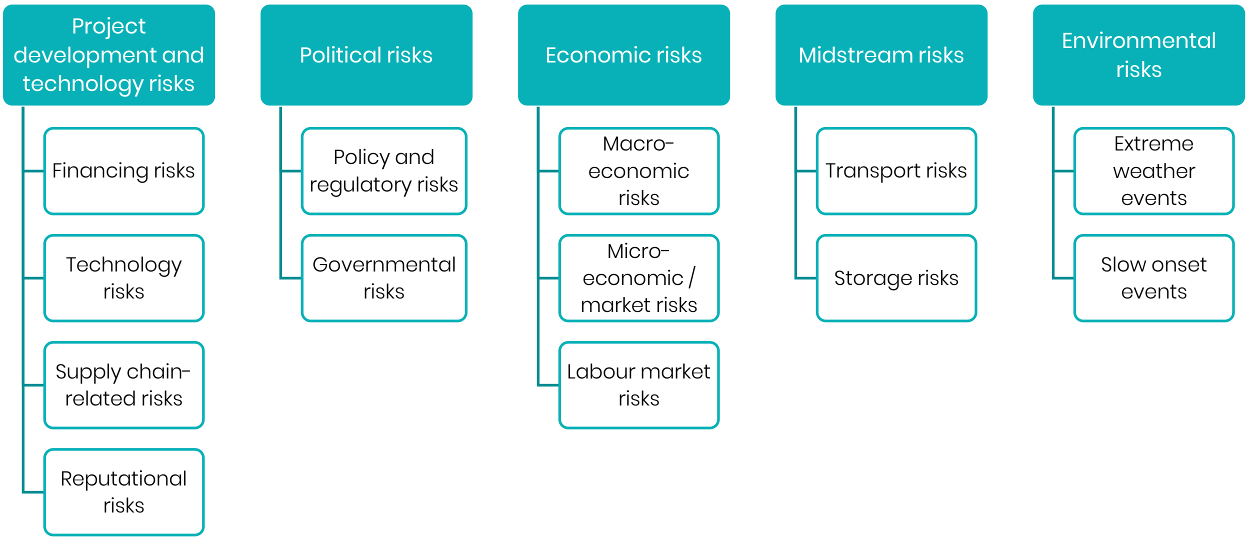

Figure 2: Identified risk dimensions and categories

Project development and technology risks

Project development and technology risks emerge throughout the entire value chain including the following:

- Financing risks
- Technology risks
- Supply chain-related risks
- Reputational risks

Financing risks

Financing risks predominantly occur in the early stages, i.e. before the operational phase, because renewable hydrogen projects, like most other renewable energy projects, have high up-front costs and therefore require reliable and preferably long-term funding in order to be successfully implemented .[10] Scarcity of financing and/or investors, which results in a **lack of capital** that can inhibit or even prevent the realisation of planned projects at an early stage, can be caused by several factors. Apart from potential restrictions to long-term bank lending, potential financers may also feel unable to assess and quantify the risks involved due to a lack of experience with renewable hydrogen technologies.

Further financing risks include unexpectedly **high costs of capital**, **insufficient financial expertise of the project partners** and **insufficient managerial know-how**. Recently, rising interest rates in combination with inflation and supply chain challenges have led to higher-than-anticipated capital costs of renewable energy projects, including hydrogen[11], highlighting the interdependence between different risk categories. These risks do not immediately prevent the implementation of a project but can have profound adverse effects at later stages. Other financing risks occurring at later stages include **refinancing risks**, e.g. no access to new capital when needed, and **legal**

[10] IEA - International Energy Agency, "The cost of capital in clean energy transitions – Analysis - IEA," 2021, https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions, accessed January 2023.

[11] RAMBOLL, "Achieving affordable green hydrogen production plants", 2023, https://brandcentral.ramboll.com/share/wxgP8n6EeW2ftLsQKAaR, accessed December 2023.

and liability risks, which refer to obligations or payments of indemnity or compensation to third parties, e.g. due to potential environmental damage. This category also covers uncertainties regarding legal disputes and contracting risks.

Technology risks
Technology risks can also arise during the lifetime of a hydrogen project. In the early stages, **inaccuracies in planning** are a major risk which may not only cause delays later on but which could ultimately threaten the successful implementation of the entire project. **Uncertainties about durability**, e.g. due to limited experience with large-scale applications of the technology, **damage to physical assets** and **defective components** can also delay the construction of the hydrogen project site or halt the production of green hydrogen.

Furthermore, **unexpected progress in alternative technologies** is also considered a technology risk as it can decrease the competitiveness of the project/the chosen green hydrogen production technology. Four main types of electrolyser technologies can be distinguished based on their operating temperature and electrolytes: while alkaline (AEL) and polymer electrolyte membrane (PEM) electrolysis are already relatively mature technologies, anion exchange membrane (AEM) and solid oxide (SOEC) have only been deployed on a limited scale so far, but are promising technologies because of their high efficiency and flexibility of operation.[12] As each of the technologies has its own advantages and drawbacks and no clear "winner" can be established, making a long-term commitment can be challenging and risky.

Supply chain-related risks
Although supply chain-related risks can be traced back to external actors, i.e. producers of components and feedstock as well as suppliers and logistics service providers, they are considered to be internal project risks in this report because they can be addressed by the project management, at least to a certain degree, through choices concerning the set-up of the project. Examples of supply chain-related risks include shortages in resources for hydrogen generation, shortages and unavailability of technological parts and replacements, and limitations in terms of infrastructure. **Insufficient green electricity supply** and **insufficient water supply** are two possible shortages of essential feedstock for hydrogen generation with severe consequences. A disruption in the supply of these or other critical resources could result in a reduced production volume or even a **forced closure of the plant**. **Disruptions during transport and construction** as well as **limitations in (supply-side) infrastructure** are further supply chain-related risks.

Reputational risks
Reputational damage is the loss of financial and social capital or market share due to the impairment of the way in which a company is perceived by relevant stakeholders. Even though such effects are often less immediately threatening to the operation of the project, research identifies corporate reputation as a crucial factor in long-term business success and survival.[13] Specific risks include **shifts in consumer preferences, stigmatisation of the product or even of the entire sector, negative stakeholder feedback** and **allegations of "green washing"**.

Political risks

Political risks are external for the project management, so it has to identify, monitor and address, without being able to directly influence or entirely avoid them. Political risks are divided into two subcategories:

- Policy and regulatory risks
- Governmental risks

Policy and regulatory risks
Policy and regulatory risks refer to an unfavourable or insufficiently clear regulatory framework for renewable hydrogen or to the design of specific hydrogen-related policies in the country of origin and/or the sales market. **Delays in permitting procedures** can constitute a bureaucratic obstacle to the planning, construction and operation of an electrolyser as well as to the coupled renewable electricity (RE) generating installation in the case of an integrated model where a single project entity

[12] IRENA, "Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal", 2020, https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction, accessed May 2021.

[13] Cheng Gao et al., "Overcoming Institutional Voids: A Reputation-Based View of Long-Run Survival", *Strategic Management Journal* 38, no. 11, 2017, accessed January 2023.

owns both the RE plant and the hydrogen facility. **Uncertainties about support schemes** concern the public financial support mechanisms available for CAPEX and/or operating expenditure (OPEX) of the electrolyser. **Uncertainties regarding sustainability requirements and certification** concern the criteria and requirements specified in the regulatory framework of the country or region in which the hydrogen is used, as these define the licensing and creditability of green hydrogen. Furthermore, **insufficient regulatory expertise** within the project management itself can exacerbate the policy and regulatory risks listed.

Governmental risks

Rather than the specific design and provisions of legislation and regulation, governmental risks address the structural and institutional dimension, such as the organisation of the state and the political system. Governmental risks cover a potentially **unfavourable change in leadership**, a **lack of democratic and constitutional principles** and **the ineffectiveness and/or unreliability of governance practices and processes**.

Economic risks

Like political risks, economic risks are beyond the control of project management. Economic risks are the effects of market dependencies and interdependencies, encompassing the following categories:

- Macroeconomic risks
- Microeconomic/market risks
- Labour market risks

Macroeconomic risks

Macroeconomic risks address the economic environment in the country in which the hydrogen is produced and/or the country of offtake. Specific macroeconomic risks include a **slowdown of economic growth**, an **increased rate of inflation/currency devaluation**, an **unfavourable development of the exchange rate** and **increasing public debt**.

Microeconomic risks/market risk

Microeconomic risks address the project's dependencies and interdependencies on the development of the market for hydrogen and other commodities. Hydrogen prices and their fluctuation as well as the hydrogen demand are decisive factors for a project's success. They also influence other risk categories – for example, a secure long-term offtake can be a prerequisite for making renewable hydrogen projects bankable. Possible microeconomic risks include **unfavourable market price developments for key components, equipment, feedstock, etc.** Particularly relevant examples include the cost of renewable electricity (adding to OPEX) and electrolysers (CAPEX). Microeconomic risks can also include **unfavourable market price developments of fossil equivalents**, **competition with other defossilisation options/energy carriers**, **lower carbon prices than expected**, **market saturation**, **lower demand than expected**, and **counterparty risks**. The latter refers, for example, to credit and default risks by a counterparty in a financial transaction.

Labour market risks

One of the main concerns of project management, especially in the case of technologically demanding tasks, is the **scarcity of skilled workers**, and green hydrogen projects are no exception to this. Due to a possible scarcity, **higher wage levels than expected** can also be an occurring risk. Furthermore, the scarcity can be exacerbated by an unavailability of **training and educational programmes**.

Midstream risks

Unlike the other risk dimensions listed above, the classification of midstream risks was not adopted from the existing literature on renewable energy projects but rather from the fossil fuel production and supply industry. In traditional fossil fuel industries such as oil and natural gas, midstream risks refer to the uncertainties linked to the processing, transport and storage of liquid or gaseous fuels.[14] The transportation and storage of hydrogen, in comparison to natural gas or crude oil, pose specific challenges and risks resulting both from hydrogen's chemical and physical properties and the lack of dedicated infrastructures. As this report focuses on hydrogen

[14] Cosimo Corsini, Sven Heiligtag, and Dieuwert Inia, "Strategic choices for midstream gas companies: Embracing Gas Portfolio @ Risk", McKinsey Working Papers on Risk No. 50, 2013, https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/risk/working%20papers/50_strategic_choices_for_midstream_gas_companies.pdf, accessed January 2023.

used in its pure form and not on derived synthetic energy carriers, the potential risks of further processing green hydrogen are not considered. Midstream risks can therefore be divided into the following categories:

- Transport risks
- Storage risks

Transport risks
Transport risks emerge in the later stages of the hydrogen value chain and are – especially as this risk report focuses on the export of hydrogen – crucial to a project's success. Hydrogen's properties, e.g. its flammability, ease in escaping from containment and ability to cause embrittlement of materials, give rise to specific challenges related to transporting and distributing it.

The examples mentioned above refer to technical and safety risks and the loss or reduction of product during transport. Other transport risks correlate with economic risks, namely insufficient transport options for hydrogen and higher transport prices than expected.

Storage risks
Storage risks are very similar to transport risks as they affect the same, later stages of the value chain. Hydrogen can generally be stored as a gas, typically in high pressure tanks, as a liquid at cryogenic temperatures of below -252.8°C, in caverns, or on the surface of or within solids (i.e. by adsorption or absorption, respectively).[15] Storage risks can be technical and safety-related but also cover the loss/reduction of product as well as insufficient storage options and higher storage prices for hydrogen than expected.

Environmental risks

In this report, environmental risks are defined narrowly, referring solely to the physical risks that result from events occurring in the physical environment and which directly impact the construction, operation or maintenance of the plant or the transport of the product. Risks linked to environmental damage caused by the hydrogen project itself, e.g. pollution or destruction, are incorporated under legal and liability as well as reputational risks. Even though such causes or events can pose broader risks or threats to society or the local population, they are not considered directly here because the risks are described from the perspective of project owners and operators, as outlined above. Therefore, the categories that fall under the dimension of environmental risks are:

- Extreme weather events (flooding, storm/cyclone, heatwaves etc.)
- Climate-related slow onset events (land and forest degradation, rise in sea level, desertification, etc.)

[15] U.S. Department of Energy, "Hydrogen Storage", 2023, https://www.energy.gov/eere/fuelcells/hydrogen-storage, accessed January 2023.

3 Defining and Selecting Test Cases

Identifying prototypical project cases with similar risk profiles

Before ranking the identified single risks, test cases to which the risks can be applied, are defined. These cases are not limited to one specific project or region but rather describe types of projects implemented under specific conditions.

As outlined in section 1, the scope of this report encompasses hydrogen produced inside and outside the EU for use/consumption within Europe. Furthermore, it focuses solely on projects for molecular green hydrogen and their associated risks and does not include risks that are specifically linked to hydrogen derivatives such as ammonia, methanol or synthetic kerosene. The restriction to gaseous renewable hydrogen also limits the potential transport routes and options and hence the potential countries of production. As gaseous transport by pipeline is the most cost-effective transport route up to a distance of 10,000 km,[16] the distances for transporting hydrogen in gaseous form to Europe are therefore taken into account when defining the test case for export-oriented projects.

As the test cases are used to represent clusters and trends for green hydrogen production, projects announced within and outside the EU – in the latter case, with a focus on export to Europe, are analysed. Several openly accessible maps for hydrogen projects exist. For example, the European Network of Transmission System Operators for Gas (ENTSOG) runs the hydrogen project visualisation platform[17], mapping renewable and low-carbon hydrogen projects in Europe, and in August 2022, the Clean Hydrogen Alliance published a list and map of over 840 viable investment projects across the hydrogen value chain and located in Europe.[18] For activities in Germany, the German Energy Agency (dena) has compiled a map of 120 projects that are either in planning, under construction or in operation.[19] For a global perspective, Pillsbury Law has created a map which tracks more than 350 blue and green hydrogen projects worldwide.[20]

Despite the differences in their scope and selection criteria for listing projects, these maps all depict emerging patterns and clusters in the distribution of renewable hydrogen projects. In Europe, regions with a high renewable electricity (RE) potential – for example the Iberian Peninsula for solar power, and coastal regions in Denmark and the Netherlands for offshore wind power – are the emerging production hubs. Germany, which has adopted ambitious targets for building up domestic renewable hydrogen production capacities, has a particularly high density of existing and announced hydrogen projects despite its small to medium RE potential.

In addition, studies and maps analysing locations with a high potential for producing renewable hydrogen have also been screened. The Fraunhofer IEE Global PtX Atlas[21] is an example of such a study with an interactive map illustrating the technical and

[16] The German National Hydrogen Council, "Hydrogen transport", 2021, https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2021-07-02_NWR-Information_Paper_Hydrogen_Transport.pdf, accessed January 2024.
[17] "Hydrogen project visualisation platform – ENTSOG", 2021, https://h2-project-visualisation-platform.entsog.eu/, accessed September 2021.
[18] European Commission, "Project pipeline of the European Clean Hydrogen Alliance", 2022, https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance/project-pipeline_en, accessed December 2023.
[19] Deutsche Energie-Agentur (dena), "Projektkarte: Vorreiter Deutschland", 2023, https://h2-dialog.info/projektkarte/, accessed December 2023.
[20] Pillsbury Law, "The Hydrogen Map: A regularly updated compendium of global low-carbon hydrogen projects and their status", 2023, https://www.thehydrogenmap.com/, accessed December 2023.
[21] Fraunhofer IEE, "Global PtX Atlas", 2023, https://maps.iee.fraunhofer.de/ptx-atlas/, accessed January 2023.

economic potential for PtX production from solar power as well as off- and onshore wind around the globe. It thus enables a differentiated examination of possible production volumes and costs at coastal and inland locations outside Europe.

Based on the analysis of announced green hydrogen project and global PtX potential, three test cases, which differ significantly in their risk profiles, are identified and selected:

- Test case 1: EU + EFTA & large-scale electrolyser (electrolyser capacity ≥ 20 MW)
- Test case 2: non-EU / EFTA & large-scale electrolyser (electrolyser capacity ≥ 20 MW)
- Test case 3: Germany + small-scale electrolyser (electrolyser capacity ≤ 1 MW)

A closer look: geographical scope of the selected test cases

Test case 1: EU + EFTA
Test case 1 includes projects in all current member states of the European Union (EU27) and the member states of EFTA:

- Iceland
- Liechtenstein
- Norway
- Switzerland

Test case 2: outside the EU / EFTA
The second test case groups together large-scale projects in countries outside the EU with a high RE potential. Specifically, it encompasses projects located in one of the following countries:

- Algeria
- Egypt
- Kazakhstan
- Libya
- Morocco
- Tunisia
- Turkey

To countercheck whether the political and macroeconomic environment in the stated countries is similar enough to group them together as part of the same test case, their scores in the Bertelsmann Transformation Indices (BTI) for Political Transformation, Economic Transformation and Governance were retrieved and compared. Although the countries' BTI performances differ, the scores are similar enough to justify clustering them, subsuming the performances in terms of the political environment under the term 'unstable', and describing the macroeconomic environment as 'challenging'. A detailed table of the countries' BTI scores across the three dimensions can be found in the appendix of this report.

Note: despite their high potential for green hydrogen production and/or the number of projects announced, the UK and Israel were excluded from test case 2 as both countries differ too much from other project locations outside of the EU in terms of their political and economic environment, and hence their risk profile, to group them together.

Test case 3: Germany
Test case 3 focuses solely on hydrogen production in Germany.

Note: the three test cases do not cover all renewable hydrogen projects located in the respective countries that fall into their geographical scope. For the additional parameters that further define their applicability and scope, see table 1.

In addition to the electrolyser site and electrolyser size, four further categories are established to define the test cases and differentiate between them: the RE potential in the region in which the projects are located, the destination or location of end-use of the hydrogen produced, the political environment and the macroeconomic environment. The indications of these six categories for each of the three test cases can be found in table 1.

	Test case 1 - EU + EFTA & large-scale	Test case 2 - Outside EU / EFTA & large-scale	Test case 3 - Germany and small-scale
Electrolyser site	Within EU or EFTA	Outside EU or EFTA	Germany
Electrolyser size/capacity	Large (≥ 20 MW)	Large (≥ 20 MW)	Small (≤ 1 MW)
RE potential*	High	High	Small to medium
Destination of hydrogen	Mainly export	Export to EU	Local use (industry and/or transport sector)
Political environment	Stable	Unstable	Stable
Macroeconomic environment	Favourable	Challenging	Favourable

Table 1: Test cases for risk assessment

* The renewable energy resource potential assessment is based on the solar, wind, hydro, geothermal, and biomass resources available in the country.

4 Risk Assessment Matrices

Ranking the identified risks by likelihood and severity for each test case

Compiling the risk assessment matrices: evaluation and ranking of identified risks

The Risk Assessment Matrix (RAM) framework, a commonly used tool to structure and inform risk management decisions[22], is used to evaluate and rank the identified risks for each of the three selected test cases.

To compile the risk assessment matrices for each of the three test cases and rank the 52 identified single risks, the following steps were conducted:

1. All 52 single risks were evaluated according to their severity and their likelihood for each of the three test cases as part of a qualitative literature-based assessment. The assessment of the risks was conducted independently by two of the authors of this report and any discrepancies were discussed until a consensus was reached. The final results were further verified through discussions with industry experts.

   The severity of the risks, for example the magnitude of consequences in the event of their occurrence, was assessed according to four possible indications ('negligible', 'marginal', 'critical', 'catastrophic'). The likelihood of occurrence of the hazard or harm linked to the respective risk was categorised by three indications as 'improbable', 'possible', and 'probable'.

2. Numerical values or scores were assigned to the respective indications to reflect the degree of severity and likelihood:

   - Negligible/improbable = 1
   - Marginal/possible = 2
   - Critical/probable = 3
   - Catastrophic = 4

By adding up the numerical values assigned to the individual risks for each test case across both dimensions, an overall risk score was deducted, which defines the allocation to, or placement in, the RAM (see Figure 3).

		Severity			
		Negligible	Marginal	Critical	Catastrophic
Likelihood	Improbable	1	1.5	2	2.5
	Possible	1.5	2	2.5	3
	Probable	2	2.5	3	3.5

Low risk	Medium risk	High risk

Figure 3: Allocation of risk scores to the Risk Assessment Matrix (RAM)

[22] Ben Ale, Peter Burnap, and David Slater, "Risk Matrix Basics", Draft for Publication 01.03.2012, https://www.researchgate.net/publication/305889949_Risk_Matrix_Basics, accessed January 2023.

Compiling the risk assessment matrices for the three test cases: placement of risk categories

As the utilisation of a risk assessment matrix comprising 52 entries would be too detailed and hinder a clear representation of individual risk rankings or placements, the ensuing matrices instead encompass the data pertaining to 2nd tier risk categories as delineated in section 2. Still, the overall risk assessment considers 3rd tier risks, taking into account both the likelihood and severity of occurrence. Consequently, numerical values for each 3rd tier risk are allocated using the previously described method for calculating the risk score. To express these values within the framework of 2nd tier risks, the numerical values of all 3rd risks associated with the respective 2nd risk are aggregated and assigned equal weights. Consequently, the scores allocated to the risk categories for each test case are derived as the mean value of their underlying individual risks.

Note: the appendix of this report contains a detailed list of the scores that were assigned to all 3rd tier single risks for each test case.

Test case 1: EU + EFTA and large-scale

As outlined in section 3, the first test case represents large scale hydrogen projects within the EU or EFTA. As these countries guarantee a high degree of political stability, the category of governmental risks constitutes the least severe and most improbable one. The single risks that fall into this category (unfavorable change of leadership, lack of democratic and constitutional principles, ineffectiveness and/or unreliability of governance) are classified as both negligible and unlikely. Even if there is a transition of power in the countries covered by test case 1, continuity is highly likely, also regarding environmental and energy policies. Market and labour market risks, transport risks and storage risks are similarly unlikely, but have a higher severity.

		Severity			
		Negligible	**Marginal**	**Critical**	**Catastrophic**
Likelihood	**Improbable**	**Governmental risks**	**Market risks** - **Labour market risks** - **Transport risks** - **Storage risks**	**Financing risks** - **Supply chain-related risks** - **Reputational risks**	
	Possible		**Technology risks** - **Policy and regulatory risks** - **Macroeconomic risks** - **Physical environmental risks**		
	Probable				

Figure 4: RAM for test case 1 (EU + EFTA & large-scale)

While governmental risks are considered improbable and negligible, policy and regulatory risks, which also fall into the category of political risks, are considered to be marginal in severity, but probable. As the regulatory framework for renewable hydrogen is only just evolving, uncertainties remain that result from a lack of clarity of legislative provisions as well as from a lack of expertise and experience with applying them. In addition, delays due to lengthy approval procedures can have a significant impact on the realisation and implementation of hydrogen projects and are therefore classified as the most severe individual risks in test case 1 in the event of their occurrence.

Similarly severe individual risks include a **lack of capital** and refinancing, both of which are **financing risks**. While a lack of capital and delays due to approval procedures can halt a hydrogen project right from the start, the refinancing risk can terminate a project in the later stages of its existence. From a project's point of view, both are catastrophic outcomes. In addition to financing risks, **supply chain-related risks** and **reputational risks** are also seen as critical and therefore as the most severe risk categories in test case 1.

In summary, a hydrogen project in the EU or EFTA is seen as risk-averse, particularly because the most severe risk categories (financing risks, supply chain-related risks, reputational risks) are project development and technology risks, which can be effectively controlled and mitigated

Test case 2: outside EU / EFTA and large-scale

The second test case encompasses large-scale hydrogen production sites outside the EU with a focus on export. As outlined in section 3, this case includes projects in seven countries characterised by comparatively unstable political and economic environments. Therefore, it is not surprising that governmental risks – in contrast to test case 1 – are found to have the most severe impact. Major uncertainties surround the political systems and continuity is not granted or at least cannot be guaranteed.

		Severity			
		Negligible	**Marginal**	**Critical**	**Catastrophic**
Likelihood	**Improbable**		**Market risks**	**Financing risks** - **Reputational risks**	
	Possible		**Macroeconomic risks** - **Labour market risks**	**Technology risks** - **Supply chain-related risks** - **Physical environmental risks** - **Policy and regulatory risks** - **Transport risks** - **Storage risks**	
	Probable			**Governmental risks**	

Figure 5: RAM for test case 2 (outside the EU / EFTA & large-scale)

It is no coincidence that market risks are placed in the same "box" of the RAM in test cases 1 and 2. This risk category refers to the sale of hydrogen and therefore – with the report's focus on EU offtakers in both test cases – on the emerging European (hydrogen) market. However, in contrast to test case 1, market risks represent the least severe risk category in the second test case.

In comparison to test case 1, more severe individual risks exist in test case 2, with delays due to approval procedures – similar to test case 1 – and insufficient fresh water supplies found to be the most serious individual risks.

An investment outside the EU contains more risks than inside the EU – at least for the countries under consideration. This is aggravated by the fact that it is difficult for the project management to mitigate the test case's most serious risk category (governmental risks) as these risks mostly fall outside its area of operation.

Test case 3: Germany and small-to-medium scale

The project site for test case 3 lies in Germany and the considered electrolyser size is small-to-medium, unlike the large-scale projects considered in test cases 1 and 2. Furthermore, the green hydrogen produced is mainly designated for local use.

With the electrolyser sites in Germany being considered, **governmental risks** are found to be the least severe risk category. Germany guarantees political stability and continuity of (energy and environmental) policies. Furthermore, transport and storage risks are ranked as marginal or negligible for test case 3 as the green hydrogen is mainly produced for local use and the development of transport routes is often not necessary.

		Severity			
		Negligible	**Marginal**	**Critical**	**Catastrophic**
Likelihood	**Improbable**	**Governmental risks** - **Transport risks**	**Market risks** - **Storage risks**	**Reputational risks** - **Financing risks**	
	Possible		**Technology risks** - **Supply chain-related risks** - **Policy and regulatory risks** - **Macroeconomic risks** - **Labour market risks** - **Physical environmental risks**		
	Probable				

Figure 6: RAM for test case 3 (Germany & small-scale)

Compared with the other two test cases, the renewable energy potential in Germany is only small to medium, which increases the risk of insufficient green electricity supply due to competition with other use cases. Another project risk which is higher in this test case compared to the other two is higher wage levels than expected. With an already high wage level in Germany, increasing wages can have severe impacts on a project's economic viability.

5 Risk Mitigation Strategies

Addressing and mitigating green hydrogen project risks

Risk mitigation strategies

Risk mitigation is chronologically the last task after identifying, assessing and ranking the risks to which a project is exposed, and involves dealing with the identified and analysed risks as well as finding practicable and economically reasonable strategies to do so. These strategies are based on the risk appetite of the parties involved, referring to the willingness to tolerate or accept certain levels of risk[23]. Four typical risk mitigation strategies have been compiled for green hydrogen projects, in consensus with risk management across sectors (see Figure 7).

Figure 7: Overview of possible risk mitigation strategies

Risk acceptance

Briefly, risk acceptance comes down to "risking it", as it does not reduce the possible negative effects. It is still considered to be a deliberate strategy, as the risks are actively acknowledged. This is appropriate and suitable when the (accepted) risk is small and unlikely to happen, and therefore the costs of other mitigation options outweigh the costs of the risk itself.

Risks with such a small impact or likelihood differ between projects and must be identified and analysed individually. For green hydrogen projects the least severe risk categories illustrated in the risk matrices in section 4 and the report's appendix can give the first hints of the acceptable risks. Thus, risk acceptance is usually applied to low risk, which represents – according to the report's methodology and as illustrated in Figure 3 – a risk score of between 1 and 1.5.

Therefore, the following risks that were ranked and classified in section 4 can be considered acceptable:

- Governmental risks: test cases 1 and 3
- Market risks: test cases 1, 2 and 3
- Transport risks: test cases 1 and 3
- Storage risks: test cases 1 and 3
- Labour market risks: test case 1

In adopting a risk acceptance strategy, it is important to emphasize that such acceptance does not imply that these risks are disregarded, but rather that strategic choices are formulated to allocate resources judiciously. This means considering the possible, albeit unlikely, occurrence of an event. It includes setting aside a contingency reserve that includes quantifiable actions in the form of time, financial capital or resources to mitigate the impact of the corresponding threat.

[23] Ernst & Young, "How to implement risk management to drive development impact", 2020, https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/consulting/ey-how-to-implement-risk-management-to-drive-development-impact-final-june.pdf?download, accessed October 2023

Risk limitation

Risk limitation is the most common risk mitigation strategy. It limits a project's exposure to an identified risk and implies a combination of risk acceptance and risk avoidance by taking countermeasures to decrease the likelihood and/or impact of consequences. Risk limitation is applied when dealing with medium to high risk, representing a risk score of between 2 and 3.5 (see Figure 3). Effective risk limitation requires comprehensive project and risk management as it involves proactive measures as well as reacting to already occurring risks.

For green hydrogen projects, possible risk limitation strategies (without claiming to be complete) include:

- Diversification
- Long-term contracts with suppliers
- Long term offtake agreements
- Predictive maintenance
- Political advocacy and interest representation
- Employee training
- Compliance guidelines
- Emergency plans and standards
- Monitoring and surveillance
- Performance tests
- Stakeholder engagement

Risk transfer

Transferring risks means handing them over to a willing third party such as a bank or insurance company. Public and international institutions can also act as a risk-limiting third party.

For a green hydrogen project, risk transfer can be particularly beneficial if a transferred risk is not a core competence of the actors involved. Furthermore, it is worth noting that risk transfer does not necessarily result in lower costs but is the best option when it can be used to reduce future damage. Similarly, to risk limitation, risk transfer is a strategy that is usually applied to medium to high risks.

Info box: risk transfer – a closer look and examples

For green hydrogen projects the following economic and political actors can serve as third-party risk-takers:

- Hydrogen off-takers and business associates
- Insurance companies
- Banks
- Public and government institutions
- International institutions

Feasible risk transfer strategies include:

Contractual provisions
- Business model: tolling vs. sale-and-purchase-model
- Payment and offtake obligations: take-or-pay vs. take-and-pay
- Penalty payments for delayed deliveries
- Performance warranties

Guarantees
- State and government guarantees (concessional finance)
- Export credit guarantees
- Partial risk and partial credit guarantees

Insurance policies
- Insurance against specific risks along the value chain (serial loss cover, cover for unscheduled downtime, etc.)
- Political risk insurance

Others
- Currency hedging instruments
- Interest rate hedging instruments
- Catastrophe bonds for natural hazards/weather derivatives
- Energy derivatives (esp. electricity)

Risk avoidance

Risks with a high severity and likelihood, resulting in a risk score of between 3 and 3.5, are best avoided. However, this risk mitigation strategy is usually the most expensive option and is not appropriate for many risks. In many cases, complete avoidance is not possible as this would cause a downturn of the entire project.

Like the strategy of risk acceptance, risk avoidance is highly project-specific. For the exemplary test cases explored in this report, governmental risk in test case 3 is an example of a risk category with high severity and likelihood.

Conventionally, risk avoidance means refraining from engaging in activities that create such risks.[24] Consequently, in the context of test case 3, the objective of avoiding governmental risk would entail a decision not to undertake the project in the named countries. However, as described above, full avoidance may not be a viable option in all circumstances. It is therefore imperative to assess whether the specific risk aligns with the predefined risk appetite, and subsequently to formulate an appropriate decision within that particular scenario.

Matching identified risks and mitigation strategies

Having identified and assessed the risks of a green hydrogen project and potential mitigation strategies, the next step is to match them to ensure a risk-resilient project.

Risks of low severity and likelihood – defined as "low risks" in section 4 – are often best accepted, while risks of high severity and likelihood – defined as "high risks" are best avoided. Since avoidance is not always a feasible mitigation strategy, the application of limitation and transfer measures is the second-best strategy for dealing with high risks. For this reason, and because risk transfer and risk limitation are a narrow definition of risk mitigation strategies, we limit the following comparison to these two mitigation strategies.

Figure 8 illustrates potential actions for risk transfer and limitation for the 1st tier risk categories identified in section 2 The exemplary risk management tools are based on a review of the literature, but are not exhaustive.[25 26 27 28 29]

Info box: mitigation of governmental risk – a closer look and examples[30 31]

Because a significant part of hydrogen production will take place in countries with a higher risk profile,[32] governmental risk significantly impacts green hydrogen projects. This is in particular the case when the risk score exceeds 1.5. Mitigation strategies for these risks are not always fully known. The following is a (far from complete) selection of possible mitigation strategies that could be applicable to renewable hydrogen projects:

Political Risk Insurance (PRI) offered by public institutions and private insurers, manages risks arising from the adverse actions — or inactions — of governments[33]

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[24] Carl L. Pritchard, "Risk Management - Concepts and Guidance", 2015, 5th edition
[25] IEA - International Energy Agency (2021).
[26] Mustafa Z. Hussain, "Financing renewable energy options for developing financing instruments using public funds", World Bank, 2013, https://documents.worldbank.org/en/publication/documents-reports/documentdetail/196071468331818432/financing-renewable-energy-options-for-developing-financing-instruments-using-public-funds, accessed January 2023.
[27] Tetiana Hilorme et al. (2019).
[28] World Bank, "Sustainable Renewables Risk Mitigation Initiative (SRMI)", 2019, https://www.worldbank.org/en/topic/energy/brief/srmi, accessed January 2023.
[29] Gianleo Frisari, Valerio Micale, "Risk Mitigation Instruments for Renewable Energy in Developing Countries: A Case Study on Hydropower in Africa", 2015, https://www.climatepolicyinitiative.org/publication/risk-mitigation-instruments-for-renewable-energy-in-developing-countries-a-case-study-on-hydropower-in-africa/, accessed January 2023.
[30] IRENA, "Renewable energy finance: Sovereign guarantees", 2020, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jan/IRENA_RE_Sovereign_guarantees_2020.pdf?rev=1b7134141aa8428cbe3c4e8fba95d00a, accessed October 2023.
[31] National Association of Insurance Commissioners, "Political Risk Insurance", 2023, https://content.naic.org/cipr-topics/political-risk-insurance, accessed October 2023.
[32] Fraunhofer ISI, "Opportunities and challenges when importing green hydrogen and synthesis products", Policy Brief, 2020, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/policy_brief_hydrogen.pdf, accessed October 2023.

Sovereign Guarantees: the government guarantees that an obligation will be met if the primary obligor defaults.

Bilateral Treaties: agreements between two governments to ensure that transactions by a company from one country are protected against political risk events initiated by the other government.

Insurances or Loans by Development Banks: Multilateral Development Banks (MDBs) are accorded a "preferred creditor status" (PCS) by their member states, which gives sovereign debt obligations to MDBs precedence over other creditors and de facto exempts them from debt restructuring.

Project development and technology risks

Financing risks

- concessional finance
- state (grants)
- parent-company guarantees

Technology risks

- insurance of physical assets
- performance warranties
- predictive maintenance

Supply chain risks

- long term PPAs,
- tolling agreement as revenue contract,
- audits

Reputational risks

CSR as basis norms and values for project development

Political risks

Policy and regulatory risks

- political advocacy and interest representation
- political risk insurances

Governmental risks

- political risk insurance (PRI)
- sovereign guarantees
- bilateral treaties
- insurance or loan by development banks

Midstream risks

Transport risks

- diversification of transportation modes
- integrated infrastructure build-up

Storage risks

- contractually agreed flexible delivery
- safety and performance guarantees

Economic risks

Macroeconomic risks

- interest rate hedges
- currency hedges

Market risks

- long-term PPAs
- take-and-pay obligation of offtakers
- credit guarantees

Labour market risks

- training
- strategic cooperation with academic institutions

Physical environmental risks

Extreme weather events

- catastrophe bonds for natural hazards,
- emergency plans and standards

Slow onset events

weather derivatives

Figure 8: Examples of mitigation strategies to address identified risks

Mitigation of green hydrogen risks: status quo and outlook

As green hydrogen markets are still evolving and manifesting themselves, products, procedures and processes for risk mitigation have not yet been standardised. Certain actors such as banks, insurance companies and national and international institutions offer a range of products and solutions for mitigating green hydrogen risks. While private actors insure or give guarantees against technological and economic risks, public institutions offer solutions against political and macroeconomic risks.

To gain insight into possible developments in the mitigation options available, it is helpful to examine the evolution of risk mitigation possibilities in the renewable energy market. This acts as a means to provide an outlook for the progression of certain mitigation strategies. While the emergence of a green hydrogen market is not directly analogous in every aspect, there are several noteworthy parallels.[34][35]

The cost of financing renewable energy has fallen significantly over time,[36] as illustrated by the 87% drop in the cost of solar electricity over the past decade.[37] This trend can in part be attributed to factors such as the reduced risk at national level and developments in the capital market, particularly within the Eurozone. In addition, diminishing technology risks and learning effects have played a key role. Effective policies to support the expansion of renewable energy sources have also contributed significantly to reducing investment risks.[38]

In addition, policy measures, such as premiums, quotas, or certificates have created a reliable demand in the development of renewable energy. Applying this to the hydrogen market, for which such support and incentive schemes are partially already implemented or are being planned at EU and national level, can serve to reduce market risks and increase the attractiveness of hydrogen projects to potential investors.

In view of the positive development of risk mitigation strategies and opportunities for renewable energy and the parallels with green hydrogen, it is still crucial to point out that since there are no "off-the-shelf" green hydrogen projects, "off-the-shelf" risk mitigation products are also rare. Almost all the risk mitigation strategies illustrated and presented in this report have to be tailor-made for each green hydrogen project. As a result, there is a lack of established precedents.

This makes risk mitigation for green hydrogen projects relatively expensive at this stage of the industry's development. A market for green hydrogen solutions will have to develop in parallel with the green hydrogen industry itself. If this succeeds and the risks are effectively allocated to those actors best equipped to manage them, the cost of green hydrogen projects can be expected to decrease significantly in the coming years.

[34] Fraunhofer ISI (2020)
[35] S. Teske et al., "Technical potential and challenges of renewable hydrogen. Issues in the global south", University of Technology Sydney – Institute for Sustainable Futures, 2022, https://www.boell.de/sites/default/files/2022-12/35-bfdw-hbs-green-hydrogen-report-hr-with-cropmarks.pdf, accessed October 2023.
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[37] Creutziger, F. et al., "Technological innovation enables low cost climate change mitigation", Energy Research & Social Science, 2023, https://doi.org/10.1016/j.erss.2023.103276, accessed December 2023.
[38] Open Electricity Economics Handbook, "Cost of Renewable Electricity", 2023, http://www.open-electricity-economics.org/book/text/06.html, accessed December 2023.

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Annex

Annex 1: BTI scores

Country	Political Transformation	Status	Nr.	Economic Transformation	Status	Nr.	Governance Index	Status	Nr.
Turkey	4,8/10	moderate autocracy	74/137	6,11/19	limited	40/137	3,98/10	weak	97/137
Kazakhstan	3,78/10	hard-line autocracy	99/137	6,04/10	limited	45/137	4,56/10	moderate	79/137
Morocco	3,58/10	hard-line autocracy	108/137	5,96/10	limited	47/137	4,84/10	moderate	69/137
Algeria	4,65/10	moderate autocracy	76/137	5,43/10	limited	68/137	4,67/10	moderate	76/137
Egypt	3,37/10	hard-line autocracy	114/137	4,89/10	very limited	82/137	3,77/10	weak	108/137
Libya	2,4/10	hard-line autocracy	133/137	2,46/10	rudimentary	129/137	2,45/10	failed	127/137
Tunisia	6,55/10	defective democracy	42/137	5,96/10	limited	47/137	5,33/10	moderate	44/137

Annex 2: Detailed risk scores for test case 1 (EU + EFTA and large-scale)

Test case	1st tier	2nd tier: risk category	3rd tier: risk	Severity	Severity_ Numerical	Likelihood	Likelihood_ Numerical	Risk_Weigh ting
1	Project developme nt and technology risks	Financial risks	Lack of capital	Catastro phic	4	Possible	2	3

1	Project development and technology risks	Financial risks	Insufficient expertise	Critical	3	Improbable	1	2
1	Project development and technology risks	Financial risks	Insufficient management know-how	Critical	3	Improbable	1	2
1	Project development and technology risks	Financial risks	Liability/legal risks	Critical	3	Possible	2	2,5
1	Project development and technology risks	Financial risks	Refinancing risks	Catastrophic	4	Possible	2	3
1	Project development and technology risks	Technology risks	Inaccuracies in early planning	Critical	3	Possible	2	2,5
1	Project development and technology risks	Financial risks	High capital costs	Catastrophic	4	Possible	2	3
1	Project development and technology risks	Technology risks	Uncertainties about durability	Marginal	2	Possible	2	2
1	Project development and technology risks	Technology risks	Damages to physical assets	Marginal	2	Probable	3	2,5
1	Project development and technology risks	Technology risks	Defective components	Marginal	2	Probable	3	2,5
1	Project development and technology risks	Technology risks	Unexpected progress in alternative technologies	Catastrophic	4	Possible	2	3
1	Project development and technology risks	Supply chain-related risks	Insufficient green electricity supply	Critical	3	Improbable	1	2

1	Project development and technology risks	Supply chain-related risks	Insufficient fresh water supply	Catastrophic	4	Improbable	1	2,5
1	Project development and technology risks	Supply chain-related risks	Disruptions during transport and construction	Marginal	2	Probable	3	2,5
1	Project development and technology risks	Supply chain-related risks	Forced closure due to unavailable resources	Critical	3	Improbable	1	2
1	Project development and technology risks	Supply chain-related risks	Limitations in infrastructure	Critical	3	Improbable	1	2
1	Project development and technology risks	Reputational risks	Shifts in consumer preferences	Catastrophic	4	Improbable	1	2,5
1	Project development and technology risks	Reputational risks	Stigmatisation of product/sector	Critical	3	Improbable	1	2
1	Project development and technology risks	Reputational risks	Negative stakeholder feedback	Critical	3	Possible	2	2,5
1	Project development and technology risks	Reputational risks	Allegations of "green washing"	Critical	3	Improbable	1	2
1	Political risks	Policy and regulatory risks	Delays due to approval procedures	Critical	3	Probable	3	3
1	Political risks	Policy and regulatory risks	Uncertainties about support schemes	Critical	3	Possible	2	2,5
1	Political risks	Policy and regulatory risks	Uncertainties regarding sustainability requireme	Critical	3	Possible	2	2,5

			nts and certification					
1	Political risks	Policy and regulatory risks	Adoption of more stringent requirements	Marginal	2	Possible	2	2
1	Political risks	Policy and regulatory risks	Insufficient regulatory expertise	Critical	3	Improbable	1	2
1	Political risks	Governmental risks	Unfavourable change of leadership	Marginal	2	Improbable	1	1,5
1	Political risks	Governmental risks	Lack of democratic principles and constitutional principles	Marginal	2	Improbable	1	1,5
1	Political risks	Governmental risks	Ineffectiveness and unreliability of regional/national governance	Negligible	1	Possible	2	1,5
1	Economic Risks	Macroeconomic risks	Slow-down of economic growth	Critical	3	Possible	2	2,5
1	Economic Risks	Macroeconomic risks	Increased rate of inflation/currency devaluation	Critical	3	Possible	2	2,5
1	Economic Risks	Macroeconomic risks	Unfavourable development of exchange rate	Marginal	2	Possible	2	2
1	Economic Risks	Macroeconomic risks	Increasing public debt	Marginal	2	Possible	2	2
1	Economic Risks	Market risks	Unfavourable market prices of green electricity	Critical	3	Possible	2	2,5

1	Economic Risks	Market risks	Unfavourable market prices of fossil equivalents	Critical	3	Improbable	1	2
1	Economic Risks	Market risks	Lower carbon prices than expected	Critical	3	Improbable	1	2
1	Economic Risks	Market risks	Oversaturation of the market	Critical	3	Improbable	1	2
1	Economic Risks	Market risks	Lower demand than expected	Critical	3	Improbable	1	2
1	Economic Risks	Market risks	Counterparty risks	Critical	3	Improbable	1	2
1	Economic Risks	Market risks	Competition with other defossilisation options/energy carriers	Marginal	2	Possible	2	2
1	Economic Risks	Labour market risks	Scarcity of skilled workforce	Critical	3	Possible	2	2,5
1	Economic Risks	Labour market risks	Higher than expected wage levels	Marginal	2	Possible	2	2
1	Economic Risks	Labour market risks	Unavailability of training and educational programmes	Marginal	2	Improbable	1	1,5
1	Physical environmental risks	Physical environmental risks	Extreme weather events	Critical	3	Possible	2	2,5
1	Physical environmental risks	Physical environmental risks	Slow onset (climate-related) events	Marginal	2	Possible	2	2
1	Midstream risks	Transport risks	Higher transport prices for hydrogen	Critical	3	Possible	2	2,5

			than expected					
1	Midstream risks	Transport risks	Insufficient transport options for hydrogen	Critical	3	Improbable	1	2
1	Midstream risks	Transport risks	Technical and safety risks throughout transport	Critical	3	Improbable	1	2
1	Midstream risks	Transport risks	Loss/reduction of product throughout transport	Marginal	2	Possible	2	2
1	Midstream risks	Storage risks	Higher storage prices for hydrogen than expected	Critical	3	Possible	2	2,5
1	Midstream risks	Storage risks	Insufficient storage options for hydrogen	Critical	3	Improbable	1	2
1	Midstream risks	Storage risks	Technical and safety risks during storage	Critical	3	Improbable	1	2
1	Midstream risks	Storage risks	Loss/reduction of product throughout storage	Marginal	2	Possible	2	2

Annex 2: Detailed risk scores for test case 2 (Outside EU / EFTA and large-scale)

Test case	1st tier	2nd tier: risk category	3rd tier: risk	Severity	Severity_ Numerical	Likelihood	Likelihood_ Numerical	Risk_Weighting
2	Project development and technology risks	Financial risks	Lack of capital	Catastrophic	4	Possible	2	3
2	Project development and technology risks	Financial risks	Insufficient expertise	Critical	3	Improbable	1	2
2	Project development and technology risks	Financial risks	Insufficient management know-how	Critical	3	Improbable	1	2
2	Project development and technology risks	Financial risks	Liability/legal risks	Critical	3	Possible	2	2,5
2	Project development and technology risks	Financial risks	Refinancing risks	Catastrophic	4	Possible	2	3
2	Project development and technology risks	Financial risks	High capital costs	Catastrophic	4	Possible	2	3
2	Project development and technology risks	Technology risks	Inaccuracies in early planning	Critical	3	Possible	2	2,5
2	Project development and technology risks	Technology risks	Uncertainties about durability	Critical	3	Possible	2	2,5
2	Project development and technology risks	Technology risks	Damages to physical assets	Critical	3	Probable	3	3
2	Project development and technology risks	Technology risks	Defective components	Critical	3	Probable	3	3
2	Project developme	Technology risks	Unexpected	Catastrophic	4	Possible	2	3

	nt and technology risks		progress in alternativ e technolog ies					
2	Project developme nt and technology risks	Supply chain-related risks	Insufficien t green electricity supply	Critical	3	Improbable	1	2
2	Project developme nt and technology risks	Supply chain-related risks	Insufficien t fresh water supply	Catastro phic	4	Probable	3	3,5
2	Project developme nt and technology risks	Supply chain-related risks	Disruption s during transport and constructi on	Critical	3	Probable	3	3
2	Project developme nt and technology risks	Supply chain-related risks	Forced closure due to unavailabl e resources	Critical	3	Possible	2	2,5
2	Project developme nt and technology risks	Supply chain-related risks	Limitation s in infrastruct ure	Critical	3	Probable	3	3
2	Project developme nt and technology risks	Reputational risks	Shifts in consumer preferenc es	Catastro phic	4	Improbable	1	2,5
2	Project developme nt and technology risks	Reputational risks	Stigmatisa tion of product/s ector	Critical	3	Improbable	1	2
2	Project developme nt and technology risks	Reputational risks	Negative stakehold er feedback	Critical	3	Possible	2	2,5
2	Project developme nt and technology risks	Reputational risks	Allegation s of "green washing"	Critical	3	Possible	2	2,5
2	Political risks	Policy and regulatory risks	Delays due to approval	Catastro phic	4	Probable	3	3,5

			procedures					
2	Political risks	Policy and regulatory risks	Uncertainties about support schemes	Critical	3	Probable	3	3
2	Political risks	Policy and regulatory risks	Uncertainties regarding sustainability requirements and certification	Critical	3	Possible	2	2,5
2	Political risks	Policy and regulatory risks	Adoption of more stringent requirements	Critical	3	Possible	2	2,5
2	Political risks	Policy and regulatory risks	Insufficient regulatory expertise	Critical	3	Possible	2	2,5
2	Political risks	Governmental risks	Unfavourable change of leadership	Critical	3	Probable	3	3
2	Political risks	Governmental risks	Lack of democratic principles and constitutional principles	Critical	3	Probable	3	3
2	Political risks	Governmental risks	Ineffectiveness and unreliability of regional/national governance	Critical	3	Probable	3	3
2	Economic Risks	Macroeconomic risks	Slow-down of economic growth	Marginal	2	Probable	3	2,5
2	Economic Risks	Macroeconomic risks	Increased rate of inflation/currency devaluation	Critical	3	Possible	2	2,5
2	Economic Risks	Macroeconomic risks	Unfavourable	Marginal	2	Probable	3	2,5

			development of exchange rate					
2	Economic Risks	Macroeconomic risks	Increasing public debt	Critical	3	Possible	2	2,5
2	Economic Risks	Market risks	Unfavourable market prices of green electricity	Critical	3	Improbable	1	2
2	Economic Risks	Market risks	Unfavourable market prices of fossil equivalents	Critical	3	Improbable	1	2
2	Economic Risks	Market risks	Lower carbon prices than expected	Critical	3	Improbable	1	2
2	Economic Risks	Market risks	Oversaturation of the market	Critical	3	Improbable	1	2
2	Economic Risks	Market risks	Lower demand than expected	Marginal	2	Possible	2	2
2	Economic Risks	Market risks	Counterparty risks	Critical	3	Possible	2	2,5
2	Economic Risks	Market risks	Competition with other defossilisation options/energy carriers	Critical	3	Probable	3	3
2	Economic Risks	Labour market risks	Scarcity of skilled workforce	Marginal	2	Improbable	1	1,5
2	Economic Risks	Labour market risks	Higher than expected wage levels	Marginal	2	Probable	3	2,5
2	Economic Risks	Labour market risks	Unavailability of training and education	Marginal	2	Probable	3	2,5

			al programmes					
2	Physical environmental risks	Physical environmental risks	Extreme weather events	Catastrophic	4	Possible	2	3
2	Physical environmental risks	Physical environmental risks	Slow onset (climate related) events	Critical	3	Probable	3	3
2	Midstream risks	Transport risks	Higher transport prices for hydrogen than expected	Critical	3	Possible	2	2,5
2	Midstream risks	Transport risks	Insufficient transport options for hydrogen	Critical	3	Possible	2	2,5
2	Midstream risks	Transport risks	Technical and safety risks throughout transport	Critical	3	Possible	2	2,5
2	Midstream risks	Transport risks	Loss/reduction of product throughout transport	Critical	3	Possible	2	2,5
2	Midstream risks	Storage risks	Higher storage prices for hydrogen than expected	Critical	3	Possible	2	2,5
2	Midstream risks	Storage risks	Insufficient storage options for hydrogen	Critical	3	Possible	2	2,5
2	Midstream risks	Storage risks	Technical and safety risks during storage	Critical	3	Possible	2	2,5
2	Midstream risks	Storage risks	Loss/reduction of product throughout storage	Critical	3	Possible	2	2,5

Annex 3: Detailed risk scores for Test Case 3 (Germany and small-to-medium scale)

Test case	1st tier	2nd tier: Risk category	3rd tier: Risk	Severity	Severity_Numerical	Likelihood	Likelihood_Numerical	Risk_Weighting
3	Project development and technology risks	Financial risks	Lack of capital	Catastrophic	4	Possible	2	3
3	Project development and technology risks	Financial risks	Insufficient expertise	Critical	3	Improbable	1	2
3	Project development and technology risks	Financial risks	Insufficient management know-how	Critical	3	Improbable	1	2
3	Project development and technology risks	Financial risks	Liability/legal risks	Critical	3	Possible	2	2,5
3	Project development and technology risks	Financial risks	Refinancing risks	Catastrophic	4	Possible	2	3
3	Project development and technology risks	Financial risks	High capital costs	Catastrophic	4	Possible	2	3
3	Project development and technology risks	Technology risks	Inaccuracies in early planning	Critical	3	Possible	2	2,5
3	Project development and technology risks	Technology risks	Uncertainties about durability	Marginal	2	Possible	2	2
3	Project development and technology risks	Technology risks	Damages to physical assets	Marginal	2	Probable	3	2,5
3	Project development and technology risks	Technology risks	Defective components	Marginal	2	Probable	3	2,5

3	Project development and technology risks	Technology risks	Unexpected progress in alternative technologies	Catastrophic	4	Possible	2	3
3	Project development and technology risks	Supply chain-related risks	Insufficient green electricity supply	Critical	3	Probable	3	3
3	Project development and technology risks	Supply chain-related risks	Insufficient fresh water supply	Catastrophic	4	Improbable	1	2,5
3	Project development and technology risks	Supply chain-related risks	Disruptions during transport and construction	Marginal	2	Probable	3	2,5
3	Project development and technology risks	Supply chain-related risks	Forced closure due to unavailable resources	Critical	3	Possible	2	2,5
3	Project development and technology risks	Supply chain-related risks	Limitations in infrastructure	Marginal	2	Improbable	1	1,5
3	Project development and technology risks	Reputational risks	Shifts in consumer preferences	Catastrophic	4	Improbable	1	2,5
3	Project development and technology risks	Reputational risks	Stigmatisation of product/sector	Critical	3	Improbable	1	2
3	Project development and technology risks	Reputational risks	Negative stakeholder feedback	Critical	3	Possible	2	2,5
3	Project development and technology risks	Reputational risks	Allegations of "green washing"	Critical	3	Improbable	1	2

3	Political risks	Policy and regulatory risks	Delays due to permitting procedures	Critical	3	Probable	3	3
3	Political risks	Policy and regulatory risks	Uncertainties about support schemes	Critical	3	Possible	2	2,5
3	Political risks	Policy and regulatory risks	Uncertainties regarding sustainability requirements and certification	Critical	3	Possible	2	2,5
3	Political risks	Policy and regulatory risks	Adoption of more stringent requirements	Marginal	2	Possible	2	2
3	Political risks	Policy and regulatory risks	Insufficient regulatory expertise	Critical	3	Improbable	1	2
3	Political risks	Governmental risks	Unfavourable change of leadership	Marginal	2	Improbable	1	1,5
3	Political risks	Governmental risks	Lack of democratic principles and constitutional principles	Marginal	2	Improbable	1	1,5
3	Political risks	Governmental risks	Ineffectiveness and unreliability of regional/national governance	Negligible	1	Possible	2	1,5
3	Economic Risks	Macroeconomic risks	Slow-down of economic growth	Marginal	2	Possible	2	2
3	Economic Risks	Macroeconomic risks	Increased rate of inflation/currency devaluation	Marginal	2	Possible	2	2

3	Economic Risks	Macroeconomic risks	Unfavourable development of exchange rate	Marginal	2	Possible	2	2
3	Economic Risks	Macroeconomic risks	Increasing public debt	Marginal	2	Possible	2	2
3	Economic Risks	Market risks	Unfavourable market prices of green electricity	Critical	3	Possible	2	2,5
3	Economic Risks	Market risks	Unfavourable market prices of fossil equivalents	Critical	3	Improbable	1	2
3	Economic Risks	Market risks	Lower carbon prices than expected	Critical	3	Improbable	1	2
3	Economic Risks	Market risks	Oversaturation of the market	Critical	3	Improbable	1	2
3	Economic Risks	Market risks	Lower demand than expected	Critical	3	Improbable	1	2
3	Economic Risks	Market risks	Counterparty risks	Marginal	2	Improbable	1	1,5
3	Economic Risks	Market risks	Competition with other defossilisation options/energy carriers	Marginal	2	Possible	2	2
3	Economic Risks	Labour market risks	Scarcity of skilled workforce	Critical	3	Possible	2	2,5
3	Economic Risks	Labour market risks	Higher than expected wage levels	Critical	3	Probable	3	3
3	Economic Risks	Labour market risks	Unavailability of training	Marginal	2	Improbable	1	1,5

			and educational programmes					
3	Physical environmental risks	Physical environmental risks	Extreme weather events	Critical	3	Possible	2	2,5
3	Physical environmental risks	Physical environmental risks	Slow onset (climate-related) events	Marginal	2	Possible	2	2
3	Midstream risks	Transport risks	Higher transport prices for hydrogen than expected	Marginal	2	Possible	2	2
3	Midstream risks	Transport risks	Insufficient transport options for hydrogen	Marginal	2	Improbable	1	1,5
3	Midstream risks	Transport risks	Technical and safety risks throughout transport	Marginal	2	Improbable	1	1,5
3	Midstream risks	Transport risks	Loss/reduction of product throughout transport	Negligible	1	Possible	2	1,5
3	Midstream risks	Storage risks	Higher storage prices for hydrogen than expected	Critical	3	Possible	2	2,5
3	Midstream risks	Storage risks	Insufficient storage options for hydrogen	Critical	3	Improbable	1	2
3	Midstream risks	Storage risks	Technical and safety risks during storage	Critical	3	Improbable	1	2
3	Midstream risks	Storage risks	Loss/reduction of product throughout storage	Marginal	2	Possible	2	2

About the Global Alliance Powerfuels

The Global Alliance Powerfuels was founded in 2018 and is backed by corporate member organisations and an international network of 23 partner institutions from research and civil society. It is coordinated by the German Energy Agency (dena). All members and partners are united by the common goal of advancing the development of sustainable markets for renewable hydrogen and its derivatives (powerfuels). Further details about the Alliance and its activities can be found at www.powerfuels.org.

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