HyDelta 2

WP3 – Risks, uncertainty, and collaboration in the hydrogen-based value chain

D3.1 – Description of the indicators, risks, collaboration opportunities and case studies of interest

Status: **Final**

Dit project is medegefinancierd door TKI Nieuw Gas | Topsector Energie uit de PPS-toeslag onder referentienummer TKI2022-HyDelta.

Document summary

Corresponding author

Corresponding author	Michele Tedesco
Affiliation	TNO
Email address	Michele.Tedesco@TNO.com

Document history

Version	Date	Author	Affiliation	Summary of main changes
1	8-Jul-2022	Jacob Janssen	TNO	First version
1.1	11-Aug-2022	Harry van der Weijde	TNO	Added section on case studies, edits to other sections
2	31-Aug-2022	Jacob Janssen, Harry van der Weijde, Thomas Hajonides	TNO	Edits based on feedback of the HyDelta internal workshop on Aug 24.
3	12-Dec-2022	Harry van der Weijde	TNO	Dutch summary added
3.1	5-Jan-2023	Harry van der Weijde	TNO	Minor edits after comments from supervisory group

Dissemination level

PU	Public	X
RE	Restricted to • Project partners including Expert Assessment Group • External entity with whom a Non-Disclosure Agreement exists	

Document review

Partner	Name
Alliander	Pascal te Morsche, Elbert Huizer, Bart Vogelzang
DNV	Rohith Nair
Stedin	Tjebbe Vroon
NBNL, Gasunie, Kiwa, DNV, TNO, NEC, Hanze	HyDelta Supervisory Group

Executive summary

The scope of WP3 within the HyDelta project is to identify – together with stakeholders – risks, uncertainties, and collaboration opportunities that are crucial to understanding deployment strategies and policy in the hydrogen value chain, in particular:

- (Quantifiable) risks and (unquantifiable) uncertainties to market participants, including OPEX risk, price risk, macro-economic systemic risks, regulatory risks, and uncertainties
- Uncertainty and risks to policy makers at various levels, including local and national authorities
- Collaboration opportunities, needs and mechanisms for the sharing of revenues between collaborating parties, as well as the sharing of risk.

The purpose of the current report is to provide a more detailed scope. An initial list of risks and uncertainties has been identified through two stakeholder workshops, and is reported in this document. These risks span a wide range. Many of the key risks to individual actors are related to value chain coordination (e.g., demand, supply or storage not materializing at the same time, leading to a disconnected value chain), but there are also important risks related to the availability of key inputs (materials, but especially labor), wider economic factors, policy and regulation. Although we were able to flag some risks as particularly important, this is based on an initial analysis only, so these assessments may change after a full quantification. For some risks, there is less consensus. The following uncertainties and risks are identified in this stage of the research:

Supply chain/coordination uncertainties and risks	• Lack of electrolyser manufacturing capacity • Labor shortages • Lack of wind energy deployment • Lack of other components • Simultaneity of value chain scale-up
Demand uncertainty	• Hydrogen demand uncertainty w.r.t. volume, quality, timing and location
Market factors	• Energy and ETS prices • Competitive condition
Change in policy, regulation, and social acceptance	• Deprioritization from the public sector • Regulatory risks • Standardization • Environmental policy • Social acceptance • Hype bubble
Other financial and project risks	• Inflation and interest rates • Refinancing risk • Cost projections • Bankruptcy • Credit risk • Rerouting costs
Other operational risks	• Safety • Physical climate change damage • Outage of transmissionand distribution infrastructure • Large-scale storage availability risks • Gas leakages

The outlined uncertainties and risks are clearly different for different types of hydrogen value chains, e.g., combined offshore wind and hydrogen production at source, backbone-connected large-scale production and industrial use of hydrogen, and local production of hydrogen with distributed take-off. Accordingly, three different case studies have been identified to quantitatively assess the risks and uncertainties. We also outline different collaboration mechanisms which can help address these risks. These will be quantitatively analysed in the case studies, using a set of three energy system models which simulate the energy system at different geographical and timescales to capture a wide range of risks and uncertainties.

Samenvatting

In WP3 van het HyDelta-project identificeren we, samen met de belangrijkste stakeholders, de risico's, onzekerheden en samenwerkingsmogelijkheden die cruciaal zijn voor het begrijpen van implementatiestrategieën en beleid in waardeketens voor waterstof. Hieronder vallen zowel (kwantificeerbare) risico's en (niet-kwantificeerbare) onzekerheden voor marktdeelnemers, waaronder bijvoorbeeld OPEX-risico, prijsrisico, macro-economisch systeemrisico, regelgevingsrisico's en onzekerheden, onzekerheid en risico's voor beleidsmakers op verschillende niveaus, waaronder lokale en nationale overheden. Samenwerking tussen stakeholders, bijvoorbeeld door het delen van informatie of door meer formele contractuele samenwerkingen zoals power purchase agreements (PPAs), kunnen helpen om deze risico's te verminderen en zijn daarom een integraal onderdeel van het onderzoek.

Het doel van het huidige rapport is om een meer gedetailleerde scope te formuleren. Een eerste lijst van risico's en onzekerheden is opgesteld op basis van twee workshops voor stakeholders; deze worden in dit document beschreven. Deze set van risico's en onzekerheden is breed. Veel van de belangrijkste risico's voor individuele actoren houden verband met de coördinatie van de waardeketen (de gelijktijdige ontwikkeling van elektriciteitsproductie, waterstofproductie, infrastructuur, opslag en waterstofgebruik). Er zijn ook belangrijke risico's die verband houden met de beschikbaarheid van belangrijke productiefactoren (waaronder materialen, en vooral menskracht), bredere economische ontwikkelingen, beleid en regelgeving. Sommige van de risico's zijn, op basis van een eerste analyse, gemarkeerd als belangrijk voor investeerders. Deze inschattingen kunnen echter veranderen na een volledige kwantificering. Over de relatieve impact van andere risico's bestaat minder consensus. In deze fase van het onderzoek worden de volgende onzekerheden en risico's geïdentificeerd:

- Risico's/onzekerheden rond coördinatie van waardeketens: vertraging in of over/ondercapaciteit van elektrolyse, offshore wind, en/of andere componenten, materiaaltekorten, personeelstekorten, etc.
- Onzekerheid over de vraag naar waterstof van verschillende kwaliteiten, op verschillende lokaties en tijdstippen.
- Andere marktfactoren: energieprijzen, ETS-prijzen, hoeveelheid competitie.
- Veranderingen in beleid, regulering, en maatschappelijke acceptatie: deprioritisering van waterstof in het publieke debat, regulering, standaardisatie, milieubeleid, maatschappelijke acceptatie, over-hyping.
- Andere financiële- en projectrisico's: schommelingen in inflatie, rente, en wisselkoersen, faillisementen, kredietrisico's, etc.
- Andere operationele risico's: veiligheidsrisico's, schade door klimaatverandering, blackouts, lekkages, etc.

De geïdentificeerde onzekerheden en risico's zijn duidelijk verschillend voor verschillende soorten waardeketens, bijvoorbeeld combinaties van offshore wind- en waterstofproductie bij de bron, grootschalige productie en industrieel gebruik van waterstof op basis van een waterstofbackbone, en lokale productie van waterstof met gedistribueerde kleinschalige take-off. Voor het vervolg van het onderzoek zijn daarom drie verschillende case studies geformuleerd waar de risico's en onzekerheden in meer detail kwantitatief en kwalitatief beoordeeld kunnen worden. We schetsen ook verschillende samenwerkingsmechanismen die kunnen helpen deze risico's te reduceren of mitigeren. Deze zullen kwantitatief worden geanalyseerd in de case studies, met behulp van drie energiesysteemmodellen die het energiesysteem op verschillende geografische- en tijdsresoluties kunnen simuleren om het brede scala aan geïdentificeerde risico's en onzekerheden te kunnen analyseren.

Table of contents

1 Introduction and scope

In this deliverable we identify risks, uncertainties, and collaboration mechanisms that need to be addressed to enable hydrogen value chain stakeholders to make investment decisions that align with what is optimal at a system level and what white spots remain. We aim to define those key risks, uncertainties, and collaboration mechanisms for hydrogen stakeholders that are not always captured by high-level integrated energy system models, but that are needed to de-risk investments.

This deliverable is the result of an internal HyDelta WP2 workshop, interviews with TNO experts and an workshop with a diverse range of HyDelta partners, as well as a workshop with a wider range of external stakeholders from industry and the public sector. In parallel, the different categories of risks have been quantitatively assessed using a series of energy system models with different levels of geographical, temporal and operational detail.

The scope of this document is necessarily limited in the following ways:

1) The list of uncertainties and risks presented here focuses on investments in energy system asset/element (i.e., uncertainties and risks that can affect the financial performance of an investment in that asset).
2) The timeline studied is relatively near-term, with a focus on risks and uncertainties to investors between 2022 and 2030.
3) At this stage, we do not make a clear separation between risks (for which all possible outcomes and their probabilities are known) and uncertainties, for which outcomes and/or probabilities are not known. Further research is necessary to assess how well uncertainties can be quantified; since some market participants have private information, this may differ by investor. For the sake of completeness, we also do not separate underlying uncertainties/risks (and their relations to each other), risk events, and outcomes, because these interact in complex ways and are not always separable.
4) We necessarily focus on the 'known' uncertainties and try to cover as many as possible of them, while acknowledging that in large infrastructure projects there will also be uncertainties (the 'unknown unknowns') that have not yet even been considered. There will also be uncertainties that have been considered, but not published in the existing literature and/or considered by the necessarily small group of stakeholders that has been consulted in this phase of the study. This assessment is therefore incomplete, but we aim to at least capture the broad categories of uncertainty that are being discussed in the sector.
5) We discuss risks and uncertainties that occur anywhere along any potential value chain for hydrogen. Not all uncertainties and risks apply in every value chain or value chain element (as a simple example, offshore electrolysis and subsequent shipping of hydrogen is much less affected by disruptions to pipeline networks than onshore hydrogen production with distributed offtake). Not all uncertainties and risks are felt by all actors in a value chain, although, often, risks do propagate up and down the value chain (e.g., a delay to the installation of production capacity is likely to also financially affect transport, storage, etc.). In our case studies, we will attempt to cover a number of different value chains, actors, and uncertainties.

2 Indicators

Uncertainties and risks in the hydrogen value chain span a wide range of factors, many of which have not been quantitatively assessed. For a fair comparison between the different types of risks, we will focus mainly on their financial implications. In our quantitative analysis, we will assess the impact of the risks and uncertainties on

- **Expected revenues and costs** of different actors in the supply chain; this includes costs to consumers, revenues and costs of electrolysis, storage, transport, etc.
- (particularly for the less quantifiable uncertainties) **Worst-case revenues and costs**
- Since worst-case outcomes are directly related to the number of different scenarios that are simulated, we also look at **financial metrics such as conditional values-at risk (CVaRs)**, i.e. the expected value of a pre-defined tail of revenue or cost metrics.
- Since some risks affect hard constraints to the hydrogen value chain, rather that necessarily affecting costs or revenues, we also look separately **at expected, worst-case, and distributions of quantities**.
- We also intend to quantify the impact of the risks and uncertainties on the range and/or distribution of **environmental effects** of the energy system, particularly CO_2 emission reduction.

Other metrics exist to capture, e.g., the social impact of risks and uncertainties beyond prices, costs, quantities, profits, and emissions. These are interesting and should be analyzed in future studies, but are not the focus of this study, as they require a very different set of methods to answer.

3 Uncertainties and risks

The following uncertainties and risks have been identified in the current stage of this research:

- Supply chain/coordination uncertainties and risks
  - Lack of electrolyser manufacturing capacity
  - Labor shortages
  - Lack of wind energy deployment
  - Lack of other components
  - Simultaneity of value chain scale-up
- Demand uncertainty
  - Hydrogen demand uncertainty w.r.t. volume, quality, timing and location
- Market factors
  - Energy and ETS prices
  - Competitive condition
- Change in policy, regulation, and social acceptance
  - Deprioritization from the public sector
  - Regulatory risks
  - Standardization
  - Environmental policy
  - Social acceptance
  - Hype bubble
- Other financial and project risks
  - Inflation and interest rates
  - Refinancing risk
  - Cost projections
  - Bankruptcy
  - Credit risk
  - Rerouting costs
- Other operational risks
  - Safety
  - Physical climate change damage
  - Outage of transmissionand distribution infrastructure
  - Large-scale storage availability risks
  - Gas leakages

3.1 Supply chain/coordination uncertainties and risks

3.1.1 Lack of electrolyser manufacturing capacity

Background: A large amount of electrolysis capacity is needed to meet Dutch and international hydrogen targets; production of electrolysers needs to scale up rapidly, both in terms of total volume, but also in the ability to produce larger-capacity electrolysers. There is a joint declaration of manufacturers to increase manufacturing capacity tenfold by 2025 [1]. The Joint Declaration sets out a target agreed by electrolyser manufacturers in Europe to increase their manufacturing capacity tenfold to 17.5 GW per annum. It also features Commission actions to put in place a supportive regulatory framework, facilitate access to finance and promote efficient supply chains. However, this still needs to be put into practice, and current lead times for electrolyser orders are long. Electrolyser production capacity for the Dutch market is currently mostly concentrated in a few locations, including especially Germany. Two risks that we identify are a) The German supply chain is sourced partially in China, which is currently facing supply chain bottlenecks due to covid. In the future, it is foreseeable that geopolitical dependencies become more critical. b) The German industry is currently facing wide shut-down due to gas shortages. It is yet unclear how this could affect delays in electrolyser manufacturing [3]. An additional unique risk the manufacturing of PEM electrolysers is the available supply of iridium [13].

Impact: This risk can cause delays in delivery of electrolysers, which will affect not just electrolysis projects but also other parts of the value chain. It can also affect the quality of electrolysers. Risks to individual actors may not be negative; e.g., hydrogen importers can benefit from a shortage of electrolysis in a particular area. This impact is potentially **high**. Current projects already face major delays in delivery and installation of electrolysers. This may improve as the sector moves to more serial production; nevertheless, we still expect a **high** change of occurrence for this category of risk.

3.1.2 Labor shortages

Background: Skilled labor is necessary in the entire hydrogen value chain. Labor and skill shortages are very relevant and present as a result of a number of factors including an ageing population. Virtually all actors that are or will be part of the hydrogen value chain are currently already feeling them. For example, the Tech Barometer [6] reports alarm bells being raised about the shortage of technical personnel. The energy transition as whole is expected by create tens to hundreds of thousands of new jobs, many of which will be located outside the Randstad [14]. It is unclear where the human resource to fill these jobs will come from, especially as the working population is shrinking, and the fossil fuel industry needs to retain most of its human resource for decommissioning and interim production until 2050.

Impact: To some extent, the shortage of labor is known and therefore not a risk; however, especially further out, it is unknown exactly where in the value chain and where in the country constraints will be most acute. This risk is therefore qualified as having a **high** chance of occurring, and a **high** potential impact on the entire value chain, as it can lead to delays, hard constraints on the number of projects that can be executed, as well as to lower quality as less qualified/experienced personnel is used.

3.1.3 Lack of wind energy deployment

Background: Wind is the main source of renewable hydrogen production, and as such is a major determinant of the availability of sufficient renewable energy. Compared to particularly larger-capacity electrolysis, wind is a much more mature technology. Nevertheless, the large planned increase in offshore wind capacity in The Netherlands and across the world still presents challenges, and delays are possible for a number of reasons. For example, will enough ships for cable laying be available? Right now, these are fully booked for a long time. To address these concerns, long-term planning is required. Another, similar concern is the timely availability of high-voltage transmission lines [2] and transformer stations [5].

Impact: In spite of being a higher TRL, this risk is still qualified as having a **high** chance of occurring, and having a **high** potential impact. It is particularly high for value chains where electrolysis is co-located and/or jointly planned with electricity production.

3.1.4 Lack of other components

Background: Like electrolysis and renewable electricity production, there may be a shortage in technologies for storage and transport of hydrogen.

Impact: We assess both the probability of occurrence and impact of this risk to be **lower** than for electrolysis and renewable electricity production, because transport is coordinated by a smaller number of (regulated) network companies with government support, and because storage is available locally in salt caverns and existing on-land facilities for storage of ammonia and other carriers.

3.1.5 Simultaneity of value chain scale-up

Background: Even if all technology is available, this is not a guarantee that different parts of the hydrogen value chain will materialize at the same time. Coordination failure is a real risk, since it can mean that different parts of the value chain are (temporarily) used at lower capacities.

Impact: Given the difficulty of coordinating complex transitions, this risk has a **high** chance of occurring. Given that even small delays in being able to operate at full capacity can make or break business cases, this risk also has a **high** potential impact. This need not be negative; individual actors in the value chain may benefit from, e.g., other types of value chain not being available.

3.2 Demand uncertainty

Background: A part of the demand for hydrogen will formed through mandates. The degree to which demand will exist above that level is still unclear. Most hydrogen demand will come from industries with heavily integrated processes. IEA and IRENA [11, 12] and others report that between 12 and 20% of the energy system will flow through hydrogen. However, the capacity of industry to absorb significant amounts of additional renewable hydrogen could require more time. This is particularly true for industrial demand, e.g., from the chemical industry. The transition to hydrogen there is only just starting, and the energy demand of the industry is determined by market forces outside The Netherlands. Substitutes are also available, depending on the application. High-temperature heating will require some hydrogen, but can also be partly supplied by other means (e.g. steam-based high temperature heat). Therefore, high-temperature heating application faces more competitive pressure. Ammonia could be imported. In the metal industry, the amount of demand from the Tata Steel plant in IJmuiden is unsure, as investment decisions are not made in The Netherlands. More generally, large consumers are often multinational companies who can relocate or cease trading because of market forces outside The Netherlands.

Impact: Both the probability and impact of this risk are **high**, although it can be mitigated by, for instance, securing anchor clients, a small group of large committed clients to start off the network. Identifying in advance which external large consumers can have for leaving could also clarify this risk. There is a particularly high impact on the backbone and high impact on the regional network operators in locations where demand is concentrated.

3.3 Market factors

3.3.1 Energy and ETS prices

Background: Price risk can be split out into three components: gas, electricity, and carbon. Gas as a negative price input risk is relevant for blue H2. For green H2 applications, low gas prices can be a risk particularly for hydrogen consumers. For example, the ceramic industry may consider switching to H2, but faces the risk that gas prices will fall again leading to unprofitable market conditions in an international playing field where other ceramics producers still use natural gas. Carbon price risk is similar to gas price risk. Electricity prices affect particularly the electrolysis stage of the hydrogen value negatively, although in the longer term hydrogen also competes with direct electrification in some application areas, so high electricity prices can potentially benefit particular hydrogen investments in specific areas. Electricity prices are currently significantly elevated compared to two years ago. This may change as a result of further renewable investment and changing geopolitical dynamics, but this is uncertain, and there is limited national control over the electricity input price. However, it is important to establish which electricity prices are relevant for hydrogen value chain participants. A significant fraction of electricity is traded through power-purchasing agreements (PPAs) and other long-term contracts, which can take a range of different forms.

Impact: Volatility in energy prices is qualified as having a **high** chance of occurring, and having a **high** potential impact in principle. However, mechanisms including long-term contracts exist which can significantly reduce this impact.

3.3.2 Competitive condition

Background: A number of different types of competition are relevant for investors in The Netherlands. These include:

- Import competition: REDIII has a proposal for targets on Renewable Fuels of Non-Biological Origin (RNFBO) for industry and the transport sector. These negotiations are ongoing. Targets seem to go down, but REPowerEU on the other hand proposes to increase the targets. This lead to uncertainty. The targets will likely determine the volumes of RFNBO we can expect by 2030 and the years thereafter. RFNBO is often seen as synonym for renewable hydrogen, but the scope of RFNBO is wider, as it also includes synthetic fuels and renewable ammonia, whose energy content is derived from renewable sources other than biomass (i.e. hydrogen from wind and sun). Meeting the targets with more renewable fuels than renewable hydrogen may pose a risk for the backbone. RFNBO-targets could be met by import of renewable ammonia reducing the need to use hydrogen for domestic ammonia production, causing redundancy in the backbone.
- Competition from gas: High risk and high impact. Meeting industry decarbonization targets by CCS and other measures that may result in disappointing demand from industry to replace current hydrogen production by renewable hydrogen.
- Competition from electricity: The European market has known applications for both hydrogen and electricity. There is only partial overlap between the two, leading to a lower impact and a lower chance of occurrence.
- Competition by application: For each application, additional competition may come from abroad and other means of fulfilling the application.

Impact: Hydrogen-based decarbonization solutions are often one out of many options for an individual actor. For all applications of hydrogen an acceptable price for the sustainable hydrogen is determined by the lowest-cost alternative (e.g. other colors and purity levels of hydrogen, other technology options) that can be made available within a similar time horizon. For most applications, these alternatives exist and in many cases these could conceivably be supplied at a lower cost. This risk therefore has a **high** probability of occurrence and a **high** impact to the entire value chain. It is also possible that substitutes are more expensive than anticipated, so this risk is not only a downside risk.

3.4 Change in policy, regulation, and social acceptance

3.4.1 Deprioritization from the public sector

Background: Economic and financing risks are also linked to other risks such as regulation. If the public sector, under pressure of shifting political preferences, shifts focus, then private sector will run back as well. Currently, the hydrogen backbone is mostly publicly funded – the fear is that it is still too risky for private sector. Guarantees, smart loans, grants and potentially other public financing mechanisms need to be designed in an effective way to keep encouraging the private sector to engage. A shift in policy focus, or simply a lack of attention, can have a large impact if it happens before the sector has reached the point where it can sustain itself. A current example of shifting policy focus is the conflict in Ukraine, which causes shifting priorities towards security rather than climate. It is unclear if a shift away from hydrogen could and will happen in the future.

Impact: Deprioritisation would, at this stage, have a **high impact**. In the more mature market of the future, it will be less important. However, given legally binding targets for carbon neutrality at different levels of government (local, national, European), a complete change in policy focus seems unlikely; high-impact realizations of this risk therefore seem **less likely**.

3.4.2 Regulatory risks

Background: Part of the supply chain including most infrastructure is in public hands, but private competition is conceivable. In both cases, regulation is necessary, but the exact form this will take is unknown. Key regulatory choices include:

- Governance: who can own what, which part of the value chain is left to the market?
- Permitting procedures. Who needs to approve new investments, who gets to comment on proposals, and how long does this process take?
- Tariff regulation. How will tariffs be regulated? Will there be a maximum like in heating?
- How are competitors regulated (electricity, gas, heat, steel, ammonia)?
- How will European legislation, such as the European Parliament delegated act 2018/2001 progress?

Impact: Regulatory frameworks can reduce risk when they are designed and implemented well. However, in the current state of the world where much is unclear about regulation, it presents a **high**-impact risk with a **high impact on individual stakeholders**. Although the overall value chain is affected by this, it is less sensitive to questions of ownership, so this risk is reduced at a system level.

3.4.3 Standardization

Background: Standards for certification are developing slowly. These standards are set at an international level. In principle, they reduce risk. However, because the Dutch sector only has partial influence over how standards are set, there is a risk that decisions will be made that adversely affect the Dutch sector.

Impact: This is a particular risk to network operators, as The Netherlands, for instance, uses materials for gas pipelines that are not used elsewhere. Regulation in this area can have a **high impact**. However, it has a **lower** level of probability than other risks.

3.4.4 Environmental policy

Background: To achieve CO_2 goals as well as other environmental policies to limit emissions of nitrogen, local air pollutants, etc. it is very likely that additional market mechanisms, taxes/subsidies and/or sustainability mandates will be implemented.

Impact: This risk has a high probability of occurrence, presenting a significant but **limited** amount of **upside** risk for the hydrogen value stream. The converse risk is that environmental policy efforts will be lower than expected; this seems unlikely given the fact that environmental targets are enshrined in law at different levels of policy, but energy security concerns could override these, e.g. in case of further conflict with major suppliers such as Russia and the Middle East.

3.4.5 Social acceptance

Background: Large projects are unlikely to be successful if they have problems with social acceptance. The public can withdraw the 'license to operate' for the sector, with lengthy permitting processes, withdrawals of political support, withdrawals of investors, and other impacts as a result. This is a particular risk to hydrogen because many of the current primary tractors are large companies such as Shell, Gasunie, and others, who are already in the public eye, and not always in a positive way. Other mechanisms by which social acceptance of hydrogen could be reduced are intensification of the current debate on hydrogen as a greenhouse gas, continual negative attention from major influences (cf. Elon Musk's recent statements)

Impact: This risk can have a **high** impact. The probability of occurrence is **difficult to assess**, and mitigation options exist; e.g., good marketing strategies by the sector as a whole can take away misconceptions about hydrogen.

3.4.6 Hype bubble

Background: Hydrogen can be an instrument towards a renewable energy future. However, as part of a transition towards a hydrogen-based (part of the) economy, it can also become a goal in itself. There is a risk of over-investing in this technology and companies becoming locked in. If alternatives appear in many of the current use-cases, the demand for hydrogen may be lower than anticipated. In industry, near-term solution with hydrogen seem likely. Electric boilers seem to be sufficiently available [7], and for hydrogen production, there are advanced plans that will lead to a capacity of 500 MW electrolysis in 2025 to several GW in 2030 [7]. In mobility, the competing alternative for long-haul heavy transport could be batteries if cost and weight decline sufficiently. In the absence of electrification, the alternative is biofuels or renewable diesel [8]. In the built environment, hydrogen could be a renewable alternative for heat pumps, district heating and/or green gas. With district heating water pipes, hydrogen could still pose an option at the source.

Impact: This is a particular risk for the individual users of hydrogen. Assuming that decisions are made based on good analysis, and that to reach climate targets a wide range of technologies are needed, this risk has a **low** likelihood of occurring in general, although there may be niche applications where it is high. Impacts **are high on individual stakeholders** but lower to the system as a whole.

3.5 Other financial and project risks

3.5.1 Inflation and interest rates

Background: Inflationary pressure could lead to additional costs from purchased goods and services. The cost of capital could rise as a consequence of rising interest rates. Conversely, deflation is a risk, too, i.e. a recession. These are macro-economic risks that hold for many projects and companies, not only hydrogen, and investors are used to dealing with them. Specifically, the structure of the projected costs and profits of a company or project determines its sensitivity to inflation and interest rates. A project where costs made now and profits made far in the future will be more sensitive to a rising cost of capital.

Impact: to be determined.

3.5.2 Refinancing risk

Background: A discrepancy can appear in refinancing packages. This will depend on the details of the loan contracts, which should be made keeping in mind refinancing possibilities. We give one hypothetical example here. Suppose the construction phase is done in partnership with a company who specializes in construction. After the construction, this company leaves the project. Changes in economic conditions have led to increased costs of capital. The project needs to be refinanced for the new partnership after the construction phase against worse terms.

Impact: to be determined.

3.5.3 Cost projections

Background: Technology cost risks are dealing with the question: are the costs of technology projected correctly? These projections are sure to be wrong. Learning rates are often more positive than expected. No one knows what an electrolyser costs today as it is all project-based.

This risk is related to the so called *Valley of death* [4]. A bottleneck may occur if the cost of getting the learning effect to make cost low enough, is too large, as we are now publicly funding our way through the valley of death – or as far as we get through it.

Impact: to be determined.

3.5.4 Bankruptcy

Background: This risk is stakeholder-specific, and needs to be addressed specifically case-by-case. It is not a direct system risk because there will be redundancy or the companies will be restarted.

Impact: to be determined.

3.5.5 Credit risk

Background: Note this is a micro-risk. Credit risk pertains to the company-level risk of credit worthiness. Also connected to the risk of countries leaving. It is good to get an image of the customers. For larger companies like Tata it may be easier to get a picture of the credit worthiness than, e.g., for high temperature heating, where there is more variation in the credit worthiness of different companies. Going concern scores exist for listed companies, which could be used as an indicator here. To get a sense of the credit risk for the hydrogen backbone and the hydrogen value chain, it could be good to get an overview of credit scores for connected companies.

Impact: to be determined.

3.5.6 Rerouting costs

Background: When building roads or infrastructure lines, it is sometimes needed to reroute pipelines. This is a spatial problem – potentially lower as there are existing infra corridors. However, local problems can still happen.

Impact: to be determined.

3.6 Other operational risks

3.6.1 Safety

Background: Safety risks are an issue in many large-scale infrastructure projects. They can be detrimental for stakeholders close to the physical infrastructure. Moreover, if the perception of safety is lost, this can affect perceptions and regulation and lead to loss of momentum.

Impact: to be determined.

3.6.2 Physical climate change damages

Background: There is a potential for increased wind yield, and increased flood risk and more potential changes in solar radiation, amongst others. Local floods could cause outages on the electricity grid [9]. If there is a lot of import of hydrogen from other countries, they could be more affected [10]. Moreover, in a future energy system with higher shares of renewables, a *dunkelflaute,* a period with little wind in the dark of winter, could lead to strongly reduced production.

Impact: to be determined.

3.6.3 Outage of transmission and distribution infrastructure

Background: In order to mitigate this risk, build redundancy may be required.

Impact: to be determined.

3.6.4 Large-scale storage availability risks

Background: Some examples of large-scale storage, like salt caverns, are currently at low TRL. Their risks will need to be separately monitored. The risk is that it will not be available in time, or that storage will have a lower performance than expected (e.g. cannot hold as much hydrogen, has lower efficiency, lower capacity). There are also social acceptance risks with storage, and, importantly, a location still needs to be found.

Impact: to be determined.

3.6.5 Gas leakages

Background: Losses in hydrogen networks are currently being investigated. Gas pipes themselves are not a new technology, but evidence on losses in large-scale hydrogen transmission and distribution grids is not yet complete enough. There is a risk that losses are higher than anticipated, e.g., because of unexpected leakages.

Impact: to be determined.

4 Collaboration opportunities

The risks and uncertainties listed above need different strategies for risk reduction and/or mitigation. In some cases, the actors in the hydrogen value chain can do this on their own. For example, interest rate risk can be mitigated by firms that buy from and/or sell to foreign parties using hedging strategies, pre-payments, etc. However, there are also risks and uncertainties that require collaboration between different actors in the supply chain. It is important to identify risks and uncertainties that:

a) affect different parties in the value chain differently, e.g., when a particular realization of an uncertain factor is financially beneficial for one party but affects another one negatively. Typical examples include electricity and hydrogen price risk, which affects buyers and sellers in opposite directions. This implies that collaboration through mechanisms such as joint ventures, PPAs, swaps, etc. can reduce risk.
b) can be reduced or hedged by a particular parties, even though other parties also see the benefits of this reduction or mitigation. Some of the safety and supply chain risks fall into this category, e.g., when particular stakeholders can increase the reliability of the entire system at a small private cost. This again implies that either collaboration through joint operation and/or planning, or through financial contracting, would be beneficial. Enforced collaboration, e.g., through standards, is another potential mechanism.
c) can be reduced through better coordination between parties. This includes coordinating investment and construction, such that all parts of the value chain are in place at the same time, but may also include coordination on human resource issues to avoid human resource risks becoming even bigger than they already are. This implies that sharing information and facilitation of coordination would help.

We aim to quantify these collaboration opportunities where possible, based on the metrics defined above, i.e. their impact on expected and tail prices (using various definitions of tails), costs, revenues, and emissions.

5 Case studies

The uncertainties and risks outlined above are clearly different for different types of hydrogen value chains. In particular, there are significant differences between combined offshore wind and hydrogen production at source, backbone-connected large-scale production and industrial use of hydrogen, and local production of hydrogen with distributed take-off. At least three different case studies are therefore necessary to quantitatively assess the risks and uncertainties listed above:

- **Case study 1: Offshore hydrogen production**, inspired by the proposed Hollandse Kust West project, where electrolysis is sited together with offshore wind, and the produced hydrogen is transported by pipeline to the on-shore hydrogen backbone for use by industry or other users, including potentially export. As this is a scenario with relatively simple infrastructure but complex options for market participation and collaboration, we will mainly use EYE modelling to analyse risks (e.g., price risks) and benefits of collaboration.

- **Case study 2: Onshore centralised hydrogen production at large scale**, including also the potential for import of hydrogen or hydrogen carriers by ship, connected to an initially local hydrogen backbone to be later connected to a national network, with centralised hydrogen storage and industrial use. This case study will be inspired by the Moerdijk industrial cluster (with proposed HyTransPort.RTM and H-vision projects), but we will also look at elements of the Noordzeekanaal area, which is unique in that there is a single very large potential user of hydrogen (Tata Steel), instead of a larger number of more equally-sized consumers. Since this is a centralised scenario that includes the option for (exogenous) hydrogen imports, we will use a combination of I-ELGAS and EYE modelling to analyse risks (e.g., of a shortfall of renewable capacity, high import prices, etc.).

- **Case study 3: Production and use of hydrogen within a distribution network**. In this case study we will look at a generic part of a distribution network where, unlike in the transmission network, infrastructure can only be used for either hydrogen or natural gas, with little to no scope for parallel infrastructure. In this case study, there is local electrolysis capacity and hydrogen use (for local industry, mobility, etc.) distributed throughout a network, which is linked by pipelines only if the entire part of the network in which they operate is switched from natural gas to hydrogen. Additional hydrogen is then also supplied through a connection between the distribution network and the backbone; without a switch to hydrogen in the distribution network, only very local pipeline transport or road transport is possible. Since this is a local case study, we will use ESSIM modelling to analyse risks (e.g., of delays somewhere in the value chain).

6 References

[1] European Commision (2022). Commission supports industry commitment to boost by tenfold electrolyser manufacturing capacities in the EU https://ec.europa.eu/commission/presscorner/detail/es/ip_22_2829

[2] WindEurope (2022). Europe's offshore wind expansion will depend on vessel availability https://windeurope.org/newsroom/news/europes-offshore-wind-expansion-will-depend-on-vessel-availability/

[3] Bloomberg (2022). Germany's Union Head Warns of Collapse of Entire Industries. https://www.bloomberg.com/news/articles/2022-07-03/germany-s-union-head-warns-of-collapse-of-entire-industries#xj4y7vzkg

[4] Hudson, J., & Khazragui, H. F. (2013). Into the valley of death: research to innovation. *Drug discovery today*, *18*(13-14), 610-613.

[5] https://www.offshorewind.biz/2021/11/25/first-hollandse-kust-zuid-offshore-substation-topside-leaves-dubai/

[6] Technische branche luidt noodklok over tekort technisch personeel | Dutch IT-channel (dutchitchannel.nl)

[7] Topsector Energie (2022). Routekaart Elektrificatie: cruciaal voor een duurzame industrie

[8] TNO (2022). Alternative energy carriers. https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/green-performance-of-ships/alternative-energy-carriers/

[9] Deltaprogramma 2021: koersvast werken aan een klimaatbestendig Nederland: https://klimaatadaptatienederland.nl/actueel/actueel/nieuws/2020/deltaprogramma-2021/

[10] Bednar-Friedl, B., Biesbroek, R., & Schmidt, D. N. (2022). IPCC Sixth Assessment Report (AR6): Climate Change 2022-Impacts, Adaptation and Vulnerability: Regional Factsheet Europe.

[11] IEA (2021). Global Hydrogen Review 2021 https://www.iea.org/reports/global-hydrogen-review-2021

[12] IRENA (2019) Hydrogen: A renewable energy perspective. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

[13] TNO (2021) Using electrolysis to produce green hydrogen at scale: Difficult, but possible. https://www.tno.nl/en/focus-areas/strategic-analysis-policy/expertise-groups/strategic-business-analysis/electrolysis/

[14] SER (2018). Energietransitie en Werkgelegenheid: Kansen voor een duurzame toekomst. Den Haag: Sociaal-Economische Raad