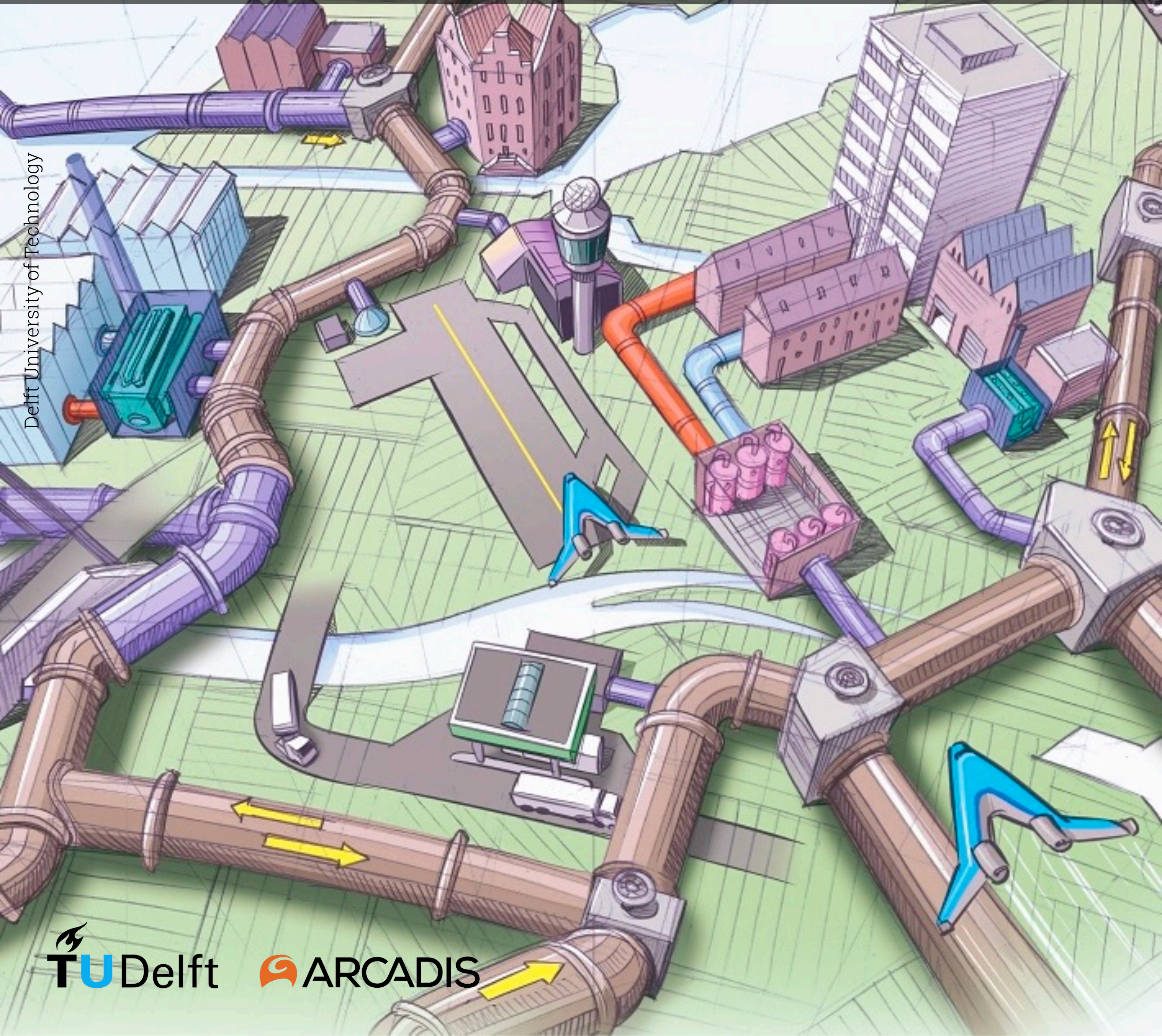
Accelerating the Development of Hydrogen Infrastructure

Addressing the Emergence of Regulatory Voids to Enable Transition Progress

Master's Thesis

J.R. (Jasper) Smit



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Accelerating the Development of Hydrogen Infrastructure

Addressing the Emergence of Regulatory Voids to Enable Transition Progress

by

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at the Delft University of Technology

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Preface

This master's thesis marks the final part of my Master's degree in Construction Management & Engineering at TU Delft, making an end to an enriching academic journey filled with learning, new experiences, and personal growth. Throughout my time at the university, I have developed skills in the fields of civil engineering and construction management, while also refining my ability to navigate complex challenges at the intersection of sustainability, governance, and technology. These interests have shaped this research's focus by reflecting broader societal and industrial challenges in navigating emerging technologies in an evolving landscape.

Both my bachelor's and master's studies have created a fascination with large-scale transitions involving complex challenges and multiple stakeholders. Among these, the energy transition, particularly the hydrogen transition, captured my interest due to the rapid technology developments and the pressing need for new market configurations and regulations. Over the past years, I have observed that there is a difference between technological advancements that need to be made and their speed of implementation. While both national and European governments have been announcing ambitious and progressive plans, the tangible impact in my immediate environment remained limited, further sparking my curiosity. Together with Moreno at Arcadis, I explored the regulatory challenges related to the hydrogen transition and identified the need for regulatory developments to support its adoption. In collaboration with Daan, I structured my graduation committee, shaping the research orientation and scope with valuable insights from Martijn and Shubham. This process ultimately led to the creation of this research, which was not possible without their guidance and support.

I would like to express my gratitude to Martijn, Shubham, Daan, and Moreno for their inspiring perspectives and invaluable feedback throughout this research. Martijn's expertise on regulatory voids has been of great value in elevating this study to a more in-depth level. In particular, I want to extend my appreciation to Shubham for our numerous interesting and inspiring discussions we have had on this topic. Some of these may have lasted longer than planned, however, these sessions have been essential in broadening my perspective and refining my approach to this thesis. I am also very grateful to Daan for his enthusiasm towards this subject and constructive feedback; which has helped make this research more comprehensive and practically relevant. A special thanks to Moreno for offering me the opportunity to conduct my research at Arcadis and to be involved in the Hy3+ project. Our sessions opened always new doors and treated new insights. Therefore introducing me to various colleagues and experts enriched this research.

Furthermore, I want to thank my family, friends, and girlfriend for their support and patiently listening to my enthusiastic stories about regulatory voids and the hydrogen transition. Even if they may not always have realised it, their conversations and feedback have been invaluable to this research.

Finally, I wish you, the reader, an engaging and insightful read. I hope you approach this report with the same enthusiasm I had while writing it. I encourage you to read it with a critical mindset; but always with a positive attitude towards contributing to the energy transition.

J.R. (Jasper) Smit
Delft, February 2025

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Executive summary

The transition towards sustainable industries is an urgent and complex challenge (European Commission, 2022a); green hydrogen holds significant potential to become a key energy carrier for storing and transporting energy (Arcadis and TNO, 2022). Urgent action is required to address environmental and societal pressures, leaving little time to delay. To integrate hydrogen into future energy systems, progress is being made in technologies like electrolysers, infrastructure, storage, and industrial processes. Alongside, supportive policies, regulations, and subsidies are developing to provide implementation and development potential (Yin, Yan, and Zhan, 2022). Despite the efforts from both industries and government sides, newly developed technologies are not easy to regulate en therefore to implement, resulting in the need to address emerging regulatory voids (Wynne, 1988). The objective of this research is to explore how these regulatory voids in transitions can be effectively addressed, focusing on answering the following research question:

”How can regulatory voids be adequately addressed concerning developing technologies related to hydrogen adoption in the Netherlands?”

In the context of energy transitions, regulatory voids are relevant since there are various emerging technologies being developed. Regulatory voids occur when existing laws and regulatory frameworks fail to address new issues, activities, or technologies (Jodi L Short, 2013a). Within the transition, this leads to ambiguity, uncertainty and potential risks which causes a slowed-down transition process (procrastination). Despite there have been many regulatory voids that emerged in past transitions, there is not an effective solution to address these voids or prevent them from happening (Wynne, 1988; Borins, 2001). This research aims to address this gap by contributing to the academic understanding while also providing solutions to address regulatory voids that are present in the hydrogen transition.

To answer the research question, the study is divided into four interrelated parts. The first part focuses on understanding how regulatory voids are defined, where they emerge, and which strategies may be applicable to address and overcome them: creating a conceptual foundation. The second part identifies regulatory voids developing within the hydrogen transition through a case study: Hy3+ (HY3+, 2024). The voids identified in the case study abductively serve as a basis for the interviews conducted with various stakeholders involved in the hydrogen transition. Together, Hy3+ case and interviews represent the primary data collection (HY3+, 2024). The third part involves analysing the primary data to identify processes and strategies that can address the identified regulatory voids. Finally, the fourth part seeks to generalise these strategies to assess their potential applicability in addressing regulatory voids in general transition contexts.

The literature review explored various aspects to establish a conceptual foundation and understanding of the emergence of regulatory voids. At this stage, regulatory voids can be defined as follows:

> *“A situation in which existing legislation and regulatory frameworks fail to adequately address or cover a specific issue, activity, or area. The absence of existing laws, regulations, or guidelines can result in ambiguity, uncertainty, and potential misuse or abuse of the situation that is created (Wynne, 1988).”*

An issue that is closely related to regulatory voids, is known as the pacing problem (Marchant, 2011a). As regulations fall behind technological advancements, bridging this gap becomes increasingly challenging, making it difficult to set (regulatory) conditions effectively. As an effect, the impact is seen in slowed down technology adoption, hesitation among stakeholders, absent guidance and thus increased complexity and risks.

Further literature studies the place where regulatory voids emerge, focusing on identifying the most critical and impactful stages where such voids are likely to develop. To analyse this, the technology development cycle was utilised, which outlines five stages of technological progression (Foxon, 2005; Grubb, 2004). The diffusion stage is the most critical, as it is often hindered by the need for regulatory revisions or the creation of entirely new frameworks to support emerging technologies. This can significantly slow down the technology adoption process to the market. The regulatory voids emerging in the diffusion stage can be defined as follows:

> *"When existing regulations fail to align with the requirements of a mature technology. Rather than an absence of regulation, these voids arise from outdated, fragmented, misaligned, or inconsistent rules and standards; leading to uncertainty, market barriers, and delays in technology deployment."*

A theory with much potential for solving and serving as guidance to address regulatory voids appears to be the institutional theory (Geels and Schot, 2007). This theory is engaging since it addresses processes based on three core elements with each their objectives that guide transitions (Scott, 1995):

- **Regulatory processes:** creation and enforcement of rules and regulations.
- **Normative processes:** idealisation of shared values, industry standards and guiding principles (subsidies among others).
- **Cultural-cognitive processes:** collective (societal) beliefs and mental models to shape the adoption.

Strategies that are relevant to address regulatory voids according to the institutional theory, are the creation of shared understanding, legitimacy, collaboration and building trust (Jeong and Kim, 2019; H.-K. Wang, Tseng, and Yen, 2014). Related to the technology diffusion stage, normative processes are especially crucial to incentivise the speed of adoption and address regulatory voids. A key factor influencing adoption costs and the ability to scale up is the economies of scale theory (George J Stigler, 1958a): as technologies scale up, production costs decrease, facilitating market acceptance.

The second and third parts of this research focus on finding the current regulatory voids in the hydrogen transition and conducting interviews with participants who are dealing with these regulatory voids. The Hy3+ case study (HY3+, 2024) offers insight into two important regulatory voids that are present in the current hydrogen adaption, each with their own specific foundation:

1. **Regulatory void market development:** the absence of a clear and structured market framework; creating uncertainty about stakeholder roles, supply chain development, and risk management, which hinders investment and adoption despite technological advancements.
2. **Regulatory void infrastructure development:** the lack of clear and coordinated regulations, particularly for the Delta Rhine Corridor (DRC), delaying network implementation and hindering progress despite readiness in hydrogen production technologies.

The regulatory voids are analysed and discussed through 20 interviews conducted with various stakeholder groups, each representing diverse backgrounds but actively engaged in the hydrogen transition. The interviews provided valuable insights into what stakeholders perceive as missing and how regulatory voids can be effectively addressed to prevent stagnation. These insights revealed overarching patterns, which were further examined through a qualitative analysis using the Gioia methodology (Gioia, Corley, and Hamilton, 2013). The key findings of this research are listed here:

- **There is limited trust and transparency among the various stakeholders** involved in the hydrogen transition, especially between the public and private parties. While on the other hand, interviewees highlight the need for collaboration to move forward. Lack of trust particularly developed due to delays in current infrastructure development plans (DRC) and events from the past. This loss of trust results in greater risks that must be taken; foremost the back-end of the supply chain lacks making investment decisions.
- Foremost hydrogen consuming stakeholders (back end of the supply chain) argue that there is a **need for a level playing field** between other parts of the world and also within Europe. The

current playing field is experienced as unequal, resulting in a 'wait and see' approach.

- Technologies are not able to develop due to **limit possibilities of scaling up**. Produced technologies, like electrolysers, lack this implementation foremost since hydrogen consumers are not taking investment decisions.
- Regulations to incentivise the hydrogen transition, like subsidies and long-term visions, **lack clarity and provide insufficient support.** European goals are not tangible enough and incentives become complex due to their applicability from various levels. Leading to a passive attitude from stakeholders to participate and FIDs are not taken therefore.
- From the analysis becomes clear that resources (e.g. subsidies) are primarily **focussed on the front end of the supply chain**. Production technologies are/have been developing(ing) and now lack implementation. The investments needed from the back end of the supply chain are too risky and too big, resulting in stagnation of the process and the need for a shift of resources.
- The need for **guidance from the national level for standards and regulations developed at EU level**. Especially for infrastructure development, there is a lack of clearly defined standards. These are currently based on the Gas directive and differ from neighbouring countries like Germany. Resulting in difficulties for cross-border connections and the development of local infrastructure in combination with among others high voltage cables and CCS-pipelines.
- The need for the **development of adaptive processes** is emphasised regarding overcoming delays that are related to transportation. Developing alternatives to pipeline transport can address current problems and create first point-to-point connections to provide transport options for the first hydrogen markets.
- One of the findings is the need for **change in government structure** related to the development of hydrogen infrastructure. A sort of principal-agent relation is developed between KGG and Gasunie that must be addressed to make infrastructural development progress.

These findings reveal challenges in stakeholder trust, regulatory clarity, and investment risks. The following takeaways suggest strategies to address these issues. Restoring trust and legitimacy is essential, requiring a collaborative environment where stakeholders work towards long-term goals and adaptively tackle complex challenges, such as the delay in the DRC. Governments should only announce plans when they are confident in their feasibility.
To address the principal-agent issue between KGG and Gasunie, financial incentives, risk-sharing mechanisms, or a neutral controlling entity could foster progress. In the short term, establishing national standards will help develop infrastructure to connect supply and demand, even if they are not fully aligned. In the long term, identifying infrastructure bottlenecks across different countries will be crucial in shaping unified European standards.
Providing comprehensive support for the entire supply chain is necessary to create a stable regulatory environment, ensuring security for back-end investments and facilitating Final Investment Decisions. Once regulatory conditions are clear and industry actors have the necessary certainty, economies of scale and technology advancements can follow, generating a market-driven feedback loop that enhances affordability and accelerates development.
Beyond market development, a more equal level playing field must be established to ensure equal investment conditions across European countries, reducing risks and enabling scaling. Addressing regulatory voids requires strong public-private collaboration, as highlighted by institutional theory. The development of tailored agreements (maatwerkafspraken) can help identify and overcome sector-specific challenges, while prioritising low-risk, financially favourable partnerships and alternative transport solutions can build market momentum and reduce project delays, such as those experienced with the DRC.

To conclude and answer the main question; a mission-driven, collaborative, and adaptive approach to regulation, resource allocation, and the development of standards is crucial for adequately addressing regulatory voids. Rather than adopting a passive point of view, regulators tend to do or react to specific issues with specific regulations. A collective public-private approach (maatwerkafspraken) will enable the implementation of technologies and drive progress. This strategy will not only provide scalability for the adoption of technologies but also create a trust-based foundation for future transitions.

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Nomenclature

Abbreviation:	**Meaning:**
ACER	Agency for the Cooperation of Energy Regulators.
AM	Adaptive Management.
CCS	Carbon Capture and Storage. A way of reducing carbon dioxide.
CEER	Council of European Energy Regulators.
DMP	Data Management Plan.
DRC	Delta Reihn Corridor.
ETS-price	Emissions Trading System Including the carbon prices to incentivise sustainable development.
EZK	Dutch Ministry of Economische Zaken en Klimaat (economic and climate affairs); new name: (see) KGG).
FID	Final Investment Decision.
GHG	Green House Gas.
IT	Institutional Theory.
KGG	Dutch Ministry of Klimaat en Groene Groei (climate and green growth).
MLP	Multi-level perspective.
NPD	New Product Development.
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency).
SNM	Strategic Niche Management.
TM	Transition Management.
TSO	Transmission System Operator, the operator of the national gas transmission grid.

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1
Introduction

The world faces immense challenges in maintaining its capacity to support human life and keep the world a place to live. As temperatures increase, sea levels continue to rise and the global population keeps growing, making it increasingly difficult to sustain this planet for future generations. In 2015, 196 countries signed the Paris Agreement, marking the beginning of a shift towards a world with net zero emissions (Paris Agreement, 2015). The signed agreement provides a rough framework to guide global efforts for decades to come: at all levels, the urge to act towards a sustainable world is gaining attention and momentum. Rules and regulations are being created to force people, businesses, and public projects to consider their impact on the world. From television adverts telling us not to take a very long shower (Mooney, 2015) to companies having to pay for CO2 pollution with so-called 'carbon credits' (Sorensen, 2023).

The transition towards renewable energy sources is of great importance in making a significant difference in the energy transition. However, sustainable innovations such as wind farms and solar panels also have negative side effects on the current energy infrastructure. Since the electricity grid is under-designed for the current capacity that it now needs to deliver, this results in the fact that the network is reaching its maximum grid capacity (Gilijamse, 2012). This implies that the integration of new renewable energy sources is constrained or impeded; this limitation also extends to the connection of new residential areas or commercial enterprises. Potential solutions may be found in the advancement of smart grids or the exploration of alternative energy carriers, with hydrogen being a prime candidate. In 2022, the EU's hydrogen strategy named REPowerEU was presented as a comprehensive framework to facilitate the uptake of renewable and low-carbon hydrogen, to decarbonise the EU (European Commission, 2022a). This framework aims to implement hydrogen in a cost-effective manner and to reduce dependence on imported fossil fuels. The EU's priority is to develop a stable renewable hydrogen market: producing 10 million tonnes and importing 10 million tonnes of hydrogen by 2030 (European Commission, 2022c). As part of reaching this goal, a European hydrogen backbone will be constructed between the Netherlands, Germany and Belgium (Arcadis and TNO, 2022), with its adoption as the central focus of the $Hy3^+$ project.

1.1. Motivation

In recent decades, the whole world has realised that if this planet must remain a liveable place for future generations, changes need to be made. The coming years will be crucial in developing and adapting to these changes. According to Vennix (2023), the gigantic energy transition can be described as "the shift from fossil fuels to renewable energy sources in an effort to reduce CO2 emissions". This will require not only new technological developments, such as the development of electrolysers or new wind farms but also changes in the services and regulations of these industries as a result of societal pressures. So the energy transition is not something that can be implemented overnight, it takes a long time to change entire systems and industries. A well-known transition from the past is the Industrial Revolution. Although it may seem much easier due to the system being considered as less complex, it took about 80 years to move from manual to machine labour. Other major revolutions, such as the use of coal and gas or the introduction of the internet were big and many lessons should have been learned by now.

However, the current energy transition is still the subject of many studies, and scholars have written papers trying to make the transition more effective and change strategic structures. A recurring theme, already described by Brian Wynne in the early 1980s (Wynne, 1988), is the existence of a regulatory gap that hinders the implementation of the transition. The widening gap between technological development and adequate regulatory development needs to be bridged to allow to accelerate progress. This challenge, though seemingly straightforward, is more complex than it appears. This academic narrative is, therefore, the central point of this thesis on the current energy transition: the speed of implementation must be maintained rather than slowed down, the pressure is now greater than ever.

1.2. Research gap

To maintain the desired speed of transitions and achieve the climate targets that have been set, the speed of technology development and adoption cannot be slowed down. As the urgency for development increases, it becomes crucial to take concrete steps to advance this technology (Arcadis and TNO, 2022). The implementation of innovations can be facilitated by establishing adequate regulations to support technical developments. This research addresses how the development of technological innovations can maintain development speed by developing adequate regulations. In other words, addressing regulatory voids to help move transitions forward.
The research gap consists of both an academic gap and a practical gap, which will be explained in the following sub-sections.

1.2.1. Academic gap

In academic literature, the problem of regulatory voids is a significant concern, especially in the context of emerging technologies. A ”regulatory void” refers to the absence of regulations for new technologies, which may lead to risks due to the lack of formal rules ensuring safety, fairness, or accountability (Bergeson, 2016). In addition, concerns about regulatory voids can give rise to feelings of instability and uncertainty, which can harm the ability of parties to embrace new developments due to apparent risks.
There are two main perspectives on how to address regulatory voids in relation to newly developed technologies. One perspective emphasises the need for exploration and innovation without immediate regulation. This perspective posits that regulations cannot be developed without a thorough understanding of the innovation. Technologies should be regarded as complex, open-ended socio-technical systems where emerging practices define rules, rather than pre-existing rules controlling practices (Wynne, 1988). The opposing perspective argues that unregulated innovations pose dangers and that rules are necessary to ensure safe development. The literature indicates that self-regulatory efforts are often unsuccessful in addressing the risks associated with regulatory voids (Jodi L Short, 2013a).
The contribution of this research to the literature is to test whether the regulatory void can be effectively addressed using existing theories, for example, institutional theory.

1.2.2. Practical problem

The development of hydrogen infrastructure, such as the European Union’s hydrogen backbone, is crucial for achieving climate targets and making progress in the energy transition. This large-scale initiative, involving multiple countries like the Netherlands, Germany, and Belgium, depends on collaboration among various stakeholders, including government institutions, grid operators, private companies, and industrial consumers. These parties are integrally connected, together forming the hydrogen supply chain and future hydrogen demand. However, the urgency of this transition therefore highlights a practical challenge: the existence of regulatory voids that hinder adoption and slow progress.
Potential regulatory voids emerge when the pace of technological and infrastructural development outpaces the creation of adequate legal frameworks and policy tools; shaping tools like regulations, norms, and standards. In the context of hydrogen development and adoption, voids might be seen in areas such as safety standards, market regulations and infrastructure standards. This regulatory uncertainty creates risks and hesitation among stakeholders, threatening the necessary speed of development and adoption.

This research aims to address the regulatory voids associated with hydrogen infrastructure adoption by exploring practical solutions to accelerate the energy transition. Specifically, it will focus on identifying and bridging these voids to potentially prevent future delays.

1.3. Research Objectives and Research Questions

The objective of this study is to explore strategies for overcoming regulatory voids and bridging the gap between rapid technological development and the slower evolution of regulatory capacity. Specifically, it aims to identify the processes necessary to construct adequate regulatory incentives that facilitate the development and adoption of emerging technologies like hydrogen. Additionally, this study investigates how insights from academic literature can be applied to address these practical challenges. Given the absence of clear guidance and fulfilment within the regulatory void, this research focuses on the following objectives, which are directly aligned with the identified research gaps:

1. To analyse the development of regulatory voids in the hydrogen energy transition and to identify strategies to address these gaps;
2. To assess the current state of the hydrogen transition within the Netherlands, focusing on technical and regulatory progress;
3. To identify tangible process steps for building regulatory frameworks supporting and accelerating the safe and efficient development of hydrogen technologies and infrastructure;
4. To create adaptable process steps that are both relevant for regulatory voids emerging in the hydrogen transition in the Netherlands and for general emerging regulatory voids within transitions.

1.3.1. Research question

This study addresses the following central question, which is supported by the research gap, identified in the previous sections.

”How can regulatory voids be adequately addressed concerning developing technologies related to hydrogen adoption in the Netherlands?”

The primary objective is to establish tangible process steps that can be implemented in regulatory frameworks to address the issue of regulatory voids. The current hydrogen transition represents an important and practical development that is directly relevant to addressing the existing regulatory voids. This research tries to discover if existing literature can address regulatory voids adequately and how these must be addressed.

The main question is divided into several sub-questions, each addressing a distinct aspect of the research question. This approach allows for a comprehensive understanding to fully answer the main question.

1. What can be done to effectively address regulatory voids?

   The objective of this first part of the research is to create a comprehensive and state-of-the-art overview of the literature on regulatory voids. First, the definition of regulatory voids will be explored in the available literature. Thereby, the place where regulatory voids will develop and emerge will be studied. Lastly, a look will be taken at regulatory development related to the type of steering methods and how regulations and policies are affecting these voids.

2. What is the status quo of the hydrogen technology development?

   It is important to gain an understanding of the current context of hydrogen development and where regulatory voids emerge. This sub-question is designed to identify specific obstacles or bottlenecks within the implementation process that are slowing down the overall transition progress. This will help to clarify the status of the hydrogen scenario and explore the policies and regulations that are active. Here, secondary data from the literature study and primary data from the case study and interviews will be used.

3. What are effective strategies on how regulatory voids can be overcome?

   This section is dedicated to the analysis of the data obtained from the first and second sub-questions to identify strategies that can address regulatory voids. By considering all the options analysed from the data, the aim is to develop process steps that support regulation and policy development to adequately address the identified regulatory voids.

4. How can the identified processes obtained from the hydrogen transition be used to address regulatory voids in general?

   The last sub-question aims to explore how lessons learned from the regulatory voids in the current hydrogen development can inform similar future transitions. Identifying effective interventions and addressing regulatory voids adequately is crucial to prevent delays in related developments.

1.4. Research Design

The research design includes both the objectives and the research questions, which are connected to the data sources that will guide the process of answering the main question. The research method and the way of collecting data will be explained in Chapters 3 and 5 respectively.

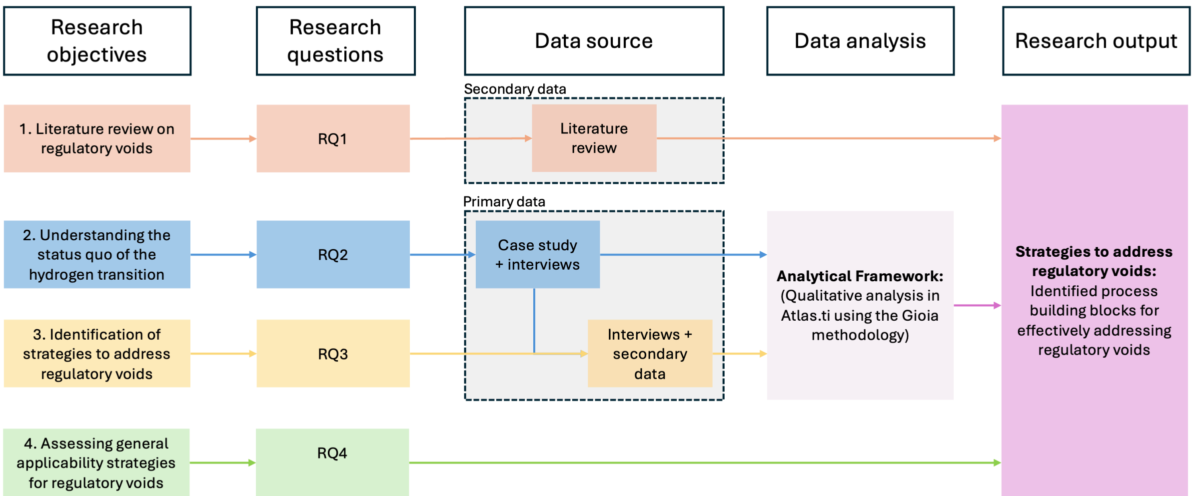

Figure 1.1: Schematic overview of the research design.

1.5. Scope

The focus of this research is to investigate regulatory voids in emerging technologies, focusing on the hydrogen transition in the Netherlands. As hydrogen technology develops, regulatory frameworks often lag, leading to uncertainties, risks, insecure investments, and thus a slowed-down adoption of sustainable energy solutions. This study tries to identify and analyse regulatory voids occurring in the hydrogen transition and propose strategies for adequately addressing these. The scope is outlined within the following points:

- **Understanding regulatory voids in the diffusion stage:**
  Defining regulatory voids and examining their emergence specifically in the diffusion stage of technological transition. Technologies that are ready for implementation but lack market adoption to create transition speed are essential to overcome.
- **Assessing the current state of hydrogen technology diffusion in the Netherlands:**
  Analyse technological advancements and infrastructure development within the diffusion stage is done in line with the Hy3[+] project. Here the regulatory voids, and bottlenecks, are identified that affect the development of regulatory voids. The hydrogen transition is particularly relevant since new technologies need to be developed to make practical implementation possible.

- **Developing strategies to address regulatory voids in the diffusion stage:**
  Investigation of stakeholders that are active within the hydrogen transition related to supply chain development. Investigating the policy mechanisms and both governance and industry strategies to gain an understanding of strategies to overcome these.
- **Providing tangible process steps to support transition development:**
  Develop adaptable process steps and interventions to support regulatory development, ensuring the safe and efficient implementation of hydrogen technologies. This research will be informed by a review of relevant literature, the $Hy3^+$ case study, and insights gathered through interviews, which will collectively shape the findings, discussion, and conclusion.

While this study primarily examines the development of new hydrogen technologies and infrastructure, as explored in the $Hy3^+$ case study in Chapter 4, the objective is not to propose new regulations to accelerate deployment. Instead, the focus is on identifying process steps that address regulatory voids and prevent delays in development.

1.5.1. Thesis outline

Figure 1.2 illustrates the structure of the different chapters to be written during the research. The outline shows the links between the chapters and their relationship to the research questions presented in section 1.3.1.

The introductory chapter, Chapter 1, presents the research topic. In Chapter 2, a review and analysis of relevant literature is conducted, with a particular focus on mapping the regulatory voids, followed by a detailed explanation of the research methodology in Chapter 3. Chapter 4 presents a single case study that deals with overcoming regulatory voids and examining the bottlenecks that are slowing down the implementation of hydrogen. This case study includes the $Hy3^+$ study that focuses on the hydrogen development between the Netherlands, Germany and Belgium (HY3+, 2024).
Chapter 5 is dedicated to data collection and analysis. The analytical lens developed from the literature and case study review will guide the interview process, through the analytical lens. Chapter 6 presents the findings from the interviews in a structured and organised manner. A double-layered approach will be taken: first via a cumulative approach general findings will be discovered, whereafter the in-depth findings will be explored.
The final part of the research includes implications and conclusions. Chapter 7 offers a discussion, emphasising the fourth sub-question. Chapter 8 concludes while Chapter 9 presents practical recommendations and (ethical) considerations.

Attachment file and its usage:
In addition to the main chapters of this research, a separate A3-format attachment is provided to enhance the understanding of key interview quotes while reading both the Findings and Discussion chapters. This attachment presents a summary of the most significant quotes, along with a comprehensive overview of the research's key findings. The content of this attachment is also included in standard format in Appendix D, Section D.5: Summary overview of Interview Instances and all the quotes are listed in Table D.2. However, due to its size and formatting, the attached file is recommended for printing purposes.

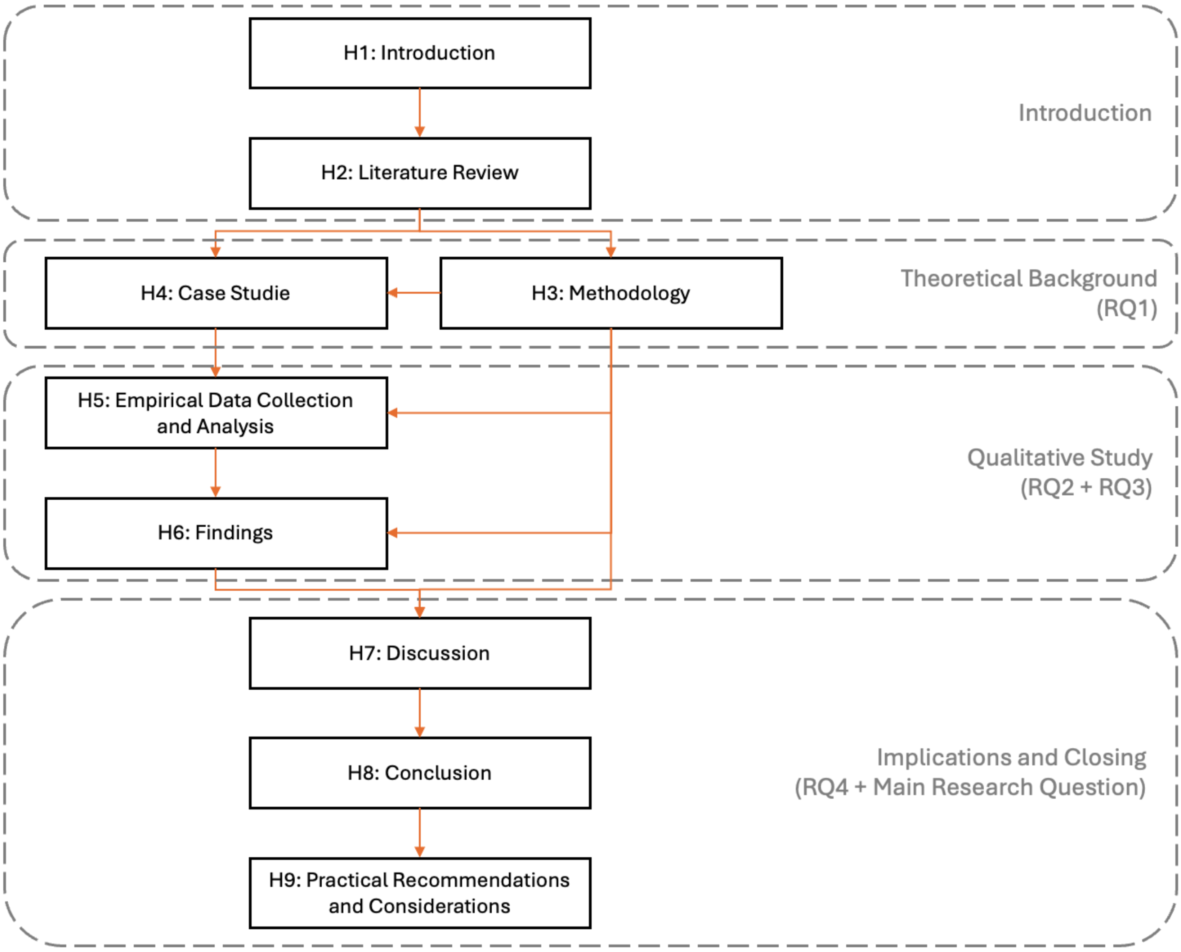

Figure 1.2: Thesis outline.

2

Literature Study

This literature study focuses on the emergence of regulatory voids and their impact on technology development. The first section establishes the conceptual foundation, exploring the nature and causes of regulatory voids. The focus then shifts to where these voids emerge within the technology development cycle, examining key stages where regulatory gaps arise. The final section delves into regulatory voids in the diffusion stage, identifying strategies and principles from existing literature on how these voids can be effectively addressed. Ultimately, this study aims to provide a comprehensive basis for answering the first sub-question of this research:

1. *What can be done to effectively address regulatory voids?*

Before diving into the literature review, an overview of the reviewed literature is provided to highlight the key findings. Figure 2.1 presents a visual representation of the literature review flow. The first part of the study focuses on establishing a general understanding of regulatory voids, addressing the 'what' aspect. The focus then shifts to identifying 'where' regulatory voids emerge within the technology development cycle. Once both dimensions are explored, the narrative is developed to integrate these perspectives ('what' + 'where'), leading to a redefinition of regulatory voids within the diffusion stage. The final part of the literature study examines strategies to effectively address regulatory voids at this stage.

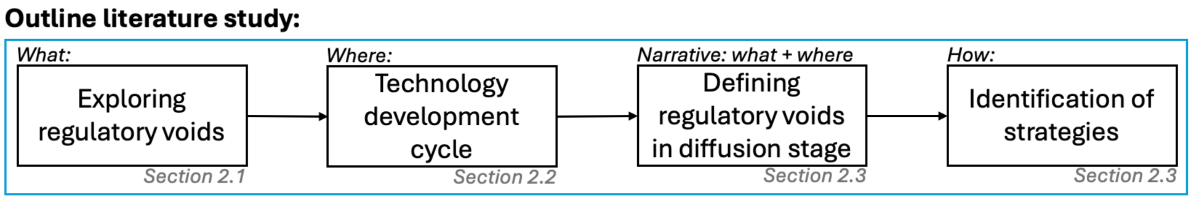

Figure 2.1: Breakdown and flow of the literature study.

Summary of literature study:
The first section of the literature study establishes a conceptual foundation for understanding regulatory voids. The term 'regulatory void' can be defined as a situation where existing legal and regulatory frameworks fail to adequately cover a specific issue, activity, or area, leading to uncertainty, ambiguity, and potential market distortions (Wynne, 1988). The emergence of regulatory voids is closely linked to the rapid pace of technological innovation, which frequently outstrips the ability of regulatory bodies to establish clear and effective governance structures. In addition, the pacing problem is introduced, which highlights the discrepancy between the speed of technological advancement and the slower pace of regulatory adaptation (Marchant, 2011a). As a result, an evolving regulatory gap emerges, growing in complexity as technology continues to develop without corresponding regulatory oversight.
Regulatory voids can create risks for industry parties, governmental institutions, technology innovators, and society. Without clear guidance, market actors may hesitate to invest in emerging technologies due to legal uncertainties, slowing down adoption and innovation (Deloitte, 2018). Additionally, the absence of regulation can lead to societal risks, such as safety concerns, ethical dilemmas, and environmental hazards, which necessitate government intervention. The conceptual foundation

provides the groundwork for understanding the significance of regulatory voids and why they must be addressed proactively.

Following the conceptual foundation, the literature review shifts focus to identifying where regulatory voids emerge within the technology development cycle (Foxon, 2005; Grubb, 2004). Technologies evolve through multiple stages, from basic research and development (R&D) to niche market introduction and eventual widespread diffusion. The most critical stage, and also the central point of this study, is the diffusion stage in which regulatory voids can develop. Here technologies have been able to fulfil all the previous stages of the technology development cycle, but are lacking market adoption. The diffusion stage is critical because regulatory voids here lead to direct delays in technology adoption, limiting the potential benefits that innovations could bring, particularly in urgent fields such as the energy transition (Lescrauwaet et al., 2022). Unlike early-stage voids, which arise from a lack of regulation, voids in the diffusion stage stem from outdated or conflicting rules that fail to accommodate new technological realities. This misalignment leads to investment hesitation, market barriers, and delays in large-scale adoption.

Given the distinct nature of regulatory voids in the diffusion stage, the research redefines the concept to reflect the unique challenges faced during this phase. Unlike the broader definition of regulatory voids, which focuses on a general absence of regulatory oversight, the diffusion-stage void is defined by regulatory misalignment rather than complete absence.

Definition 4: *Regulatory void in diffusion stage*

When existing regulations fail to align with the requirements of a mature technology. Rather than an absence of regulation, these voids arise from outdated, fragmented, misaligned, or inconsistent rules and standards; leading to uncertainty, market barriers, and delays in technology deployment.

This redefinition highlights that regulatory voids in the diffusion stage are not from a lack of speed but from a misalignment between regulations and the technology itself. Despite being mature, tested, and ready for adoption, the technology faces regulatory frameworks that are outdated, inconsistent, or ill-suited to its integration. This misalignment creates significant barriers and complexities related to multi-level governance in addressing regulatory voids in the diffusion stage (Henkel et al., 2017). Regulatory inconsistencies across jurisdictions, like variations in policies among European countries, can result in fragmented markets, regulatory uncertainty, and lowered investor confidence, further delaying widespread adoption.

The final part of the literature study focuses on identifying strategies to effectively address regulatory voids that emerge in the diffusion stage of technology development. These voids arise when existing regulatory frameworks fail to accommodate mature, market-ready technologies, creating barriers to stimulate adoption. Two key concepts play a crucial role in overcoming these voids: economies of scale and institutional theory, each offering distinct yet complementary perspectives on facilitating regulatory alignment and technology integration.
Economies of scale refer to the cost advantages gained as the production of a good or service increases. In the context of technology diffusion, scaling up production and deployment can significantly lower costs, making the technology more competitive and attractive for widespread adoption (Kenton, 2024; George J Stigler, 1958a). However, regulatory voids in the diffusion stage can prevent economies of scale from being realised, as unclear or misaligned regulations create uncertainty for investors, manufacturers, and consumers.
The institutional theory provides a framework for understanding the social, political, and organisational structures that shape regulatory environments (Huxley, Owen, and Chatterton, 2019; Scott, 1995). Institutional theory explains how regulations, norms, and cognitive frameworks influence the adoption of new technologies, and it offers insights into how regulatory voids in the diffusion stage can be effectively addressed. According to institutional theory, three key processes shape regulatory adaptation and the integration of new technologies:

- **Regulative processes:** the formation and the creation of rules, regulations and laws. These can be formal (enforced) rules to set out explicitly how things must be done. Predominantly these are imposed by the various levels of government or authoritative actors. The processes rely on legal mandates to shape behaviour and enforce compliance.

- **Normative processes:** Relate to how things should be done by setting standards, providing guidance and identifying the best practice. This process is focused on acceptable, appropriate behaviour, and on shared values.

- **Cultural-cognitive processes:** Shared beliefs, mental models and ways of thinking to shape how individuals, organisations, actors and governments understand the world and their place within it. Generating the assumption about how things are done.

By applying institutional theory, regulatory voids in the diffusion stage can be addressed through a combination of policy reform, industry collaboration, and public-private engagement. Key mechanisms such as shared understanding, legitimacy, collaboration, and trust play a crucial role in bridging these voids (Jeong and Kim, 2019). Informal norms and industry benchmarks help guide behaviour in the absence of clear regulations, while legitimacy ensures that new technologies gain acceptance and credibility (Hardt, 2013). Collaboration between public and private stakeholders fosters regulatory alignment, reducing uncertainty and enabling market integration. Additionally, trust and reputation are crucial in making investment decisions in line with adopting new technology development. By integrating these elements, the institutional theory provides a framework to address regulatory voids within the diffusion stage.

2.1. Understanding regulatory voids: conceptual foundation

The goal of this literature study is to develop a complete understanding of regulatory voids. Before examining where these voids emerge, therefore, it is essential to first establish a clear conceptual foundation. This section focuses on defining and understanding the nature of regulatory voids as a basis for further analysis.

The development of innovative technologies is not introduced from one day to another, years can go by before a technology is even developed and implemented in the system. As technologies evolve over time, there is a continual necessity for regulatory amendments to validate new developments. However, the innovations are not always clear to the outside world and can be hard to understand. Implying that the regulations are always lagging behind the development itself. However, new developments must, among other things, occur safely and protect for example the society from potential danger, which is challenging to define in advance of the new development. It is thus unclear what type of regulations governments need to implement to support safe development whilst simultaneously protecting society from potential risks associated with new technologies.
Wynne addressed the issue of stagnation and not being able to regulate processes, in a paper published in 1988; proposing that rule-following behaviour is defined by emerging practices rather than the other way around (Wynne, 1988). This implies that rules do not necessarily control practices, as is commonly assumed. Instead, practices influence the formation of rules, creating a dynamic and evolving system of regulation and compliance. This is particularly relevant in the case of technologies that are viewed as extensive, open-ended technical-social systems, where local behaviour is not easily predictable due to the lack of overall rationality (Wynne, 1988). This can result in the emergence of impractical rules, as local nationalities shape the normalisation of working technologies.

Since technological development is progressing faster than regulations can be established, regulatory bodies often lack the understanding of what needs to be regulated, resulting in a gap: a regulatory void. The direct translation of 'void' is a '(large) hole' or 'empty space' (C. Dictionary, 2019). Implying that there is a technology requiring regulation, but there is no clear guidance on how to address this gap. The term 'regulatory void' (Jodi L Short, 2013a), which can be defined as follows when taking developing technologies into account as well:

Definition 1: *Regulatory void (conceptual)*

A situation in which existing legislation and regulatory frameworks fail to adequately address or cover a specific issue, activity, or area. The absence of existing laws, regulations, or guidelines can result in ambiguity, uncertainty, and potential misuse or abuse of the situation that is created.

As the definition of the regulatory voids expresses, the inability of the regulatory institutions to adequately steer the net innovations can result in unsafe and harmful situations. The Challenger space shuttle disaster provides an illustrative example of a regulatory void (Wynne, 1988). The failure of the O-rings in the Challenger disaster was precipitated by the loss of elasticity in the rubber seals within the rocket boosters, which were designed to prevent the escape of hot gases (Harish, 2019). The loss occurred due to the unusually low temperatures on that specific day of the launch, which allowed the hot gases to escape and resulted in the explosion 73 seconds after lift-off. This is evident in the absence of clear regulatory oversight or specific guidelines governing the evaluation and mitigation of risks associated with the shuttle's boosters under extreme cold weather conditions.
The disaster shows that the regulations did not protect the safety of the launch. In the absence of testing and therefore regulatory guidance, procedures would inevitably change. In addition, the conditions deviated from the test weather temperatures and the regulations should have stopped the launch. Especially when we know that the engineers were concerned about the performance of the rings and their warnings were overruled due to the increased pressure.

2.1.1. Regulatory void development: increased challenges over time

Regulatory voids primarily arise because technological advancements outpace the development of corresponding regulations. This misalignment means that new technologies often emerge in a space without clear regulatory frameworks. A key concept that explains this dynamic is the pacing problem, which describes the gap between the rapid pace of technological innovation and the slower process of regulatory adaptation. Harris (2019) and Marchant (2011a) define the pacing problem as follows:

Definition 2: *Pacing problem*

"The growing gap between the pace of science and technology and the lagging responsiveness of legal and ethical oversight society relies on to govern emerging technologies; resulting in a potential regulatory void."

As technological developments cannot be adequately covered at the time of development, a regulatory gap is created. Related to this gap is the problem of pacing, which addresses the size of the regulatory gap. If the gap is not properly addressed in a current situation, but development continues, the gap will grow in an abstract form. Since the pacing problem evolves over time, as do technologies and regulations, two types of pacing problems can be identified: the pacing problem of now and the pacing problem of the future.

The present regulatory void

So, taking into account that technological change consistently outpaces the development of regulatory guidance, it is clear that a gap exists in the formulation of regulations and technology development. In the short term, this means that the pace of technological advancement is always ahead of the necessary regulatory and political adjustments required to effectively guide technological development.
Technology is advancing at an unprecedented rate, introducing new developments that did not exist before. As these new technologies emerge, it is almost impossible to immediately create regulations that fit the unique characteristics of these developments (Marchant, 2011a). Conversely, it is almost impossible for governments, for example, to make regulations that fit technological developments, simply because governments do not have such a predictive ability.
Regulatory development is there or it is not there, a regulation cannot be half in place. So at a certain point, there is the technological development with no regulation, and at the other point, there is regulation. This regulation can fit the technology development, not in between. This has something to do with the correctness of regulatory development, which will be discussed in Section 2.1.3.
As an example of regulatory development, the rapid rise of artificial intelligence (AI) can be taken into

account. Artificial intelligence and machine learning have outpaced current regulations and laws. This will lead to gaps in areas such as privacy, ethical use and who is accountable. The ongoing cycle of innovation outpacing regulation is creating immediate pressure to address the regulatory gaps that are emerging.

The future regulatory void:
When considering the pacing problem in a small interval of time, there is a relative consistency difference. However, when taking the progressing time into account, the issue of pacing becomes increasingly differentiated. As technological innovations continue to outpace the existing regulations, it will become increasingly challenging to maintain pace with the accelerating pace of change. One of the reasons why this is happening is due to the fact that government bodies lack the time to validate the regulations that were previously established. As a result, the increasing complexity of technology developments renders it increasingly challenging for governments to intervene effectively. The rapid pace of change makes it increasingly difficult to identify and regulate emerging issues, further complicating the regulatory process. This can be conceptualised as a snowball rolling down a mountain, gaining momentum and size as it keeps on accelerating, ultimately becoming uncontrollable. In the future, the regulatory void created by technological innovation is likely to become more significant.

2.1.2. The growing 'size' of the regulatory void

Both the ’present pacing problem’ and the ’future pacing problem’ illustrate that regulation will rarely perfectly align with (new) technological developments, creating a gap that is increasingly harder to overcome. Over time, regulatory development tends to follow a staggered progression: initially, regulations are absent, but they are later introduced in a substantial (and at times overly excessive) manner. In an ideal world, regulatory development would progress in tandem with technological advancements. This would ensure that emerging technologies are properly regulated, making them safe for implementation and societal use (Deloitte, 2018). However, in reality, this is rarely the case; regulators often struggle to keep up with disruptive technological innovations, while investors and societal pressures continue to push forward regardless of regulatory progress.

As regulatory voids expand over time, they become thus increasingly complex to address. Policy changes, as well as the formulation and implementation of regulations, do not occur incrementally over time—they either exist or they do not. The staggered nature of regulatory development stems from its inherent complexity. This results in a staggered trajectory when considering policy development for specific technologies: at one point, there is no regulation, and at another, regulatory frameworks are introduced to address technological shifts. Meanwhile, technological change itself often follows an exponential trajectory, continuously evolving and improving at an accelerating pace. The growing gap between regulatory and technological development highlights the broader issue of regulatory gaps.
Despite ongoing technological progress, the need for regulation remains critical in preventing the gap from widening further. To potentially achieve this, a more adaptive regulatory approach is for example necessary. Flexible regulatory methodologies, such as regulatory sandboxes, allow for controlled experimentation while maintaining oversight. These frameworks provide a balance between innovation and governance, enabling regulation to better align with technological progress (Fenwick, Kaal, and Vermeulen, 2016).

2.1.3. Addressing the size of regulatory voids

The existence of regulatory voids is, to some extent, inevitable. As technology continues to advance, there will always be a need for regulatory frameworks to provide guidance and oversight. It is crucial to minimise the gap between technological change and political or regulatory adaptation to prevent it from becoming bigger. Particularly in the long term, regulatory institutions need to strive to keep pace with technological developments, ensuring they understand emerging innovations and can respond effectively.

To accelerate the pace of rule-making, Marchant suggests several legal and regulatory interventions that provide a more flexible and adaptive system (Marchant, 2011b). The first proposed intervention is the acceleration of the rule-making process, which addresses the lengthy, complex analytical and procedural requirements of the current technology development process. By streamlining the rule-making process, a body can issue a final rule without going through public comment; however, should significant opposition emerge, the rule will be withdrawn and the full notice-and-comment rule-making process will be initiated (Levin, 1995). Another relevant intervention to keep pace with technological developments is conducting more periodic reviews of technology in combination with regulations. Implementing mandatory periodic reviews allows for the assessment of the current status of the regulated development and the evaluation of whether further development poses a potential risk. Thirdly, regulatory bodies must become increasingly adaptive in managing technological developments. In adaptive management regarding regulation, it is crucial to create a continual feedback loop to adjust policy in parallel with changing innovations. Additionally, using principle-based regulation involves the promulgation of general principles of expected behaviour in the sectors rather than making regulations based on specific details. Regulated parties are expected to implement these general principles in their own regulatory programmes. Focusing more on general principles rather than details will result in greater flexibility for adjustments in response to new developments. Three mechanisms that can help decrease the size of the regulatory voids are described here.

1. Strict- versus self-regulation to develop technologies:
Something that both Marchant (2011b) and Wynne (1988) explain in their papers, is the hypothesis that regulatory voids also can be addressed by self-regulating. This is also known as cooperative regulation, something that in recent years regulating bodies like the US Environmental Protection Agency and the Occupational Safety and Health Administration have applied. Here the involved industries have relied on approaches under which the industry self-regulates under the supervision of the relevant regulating body (Pedersen, 2001). EU member states apply this method also more frequently (Falkner, 2005), for example in the Netherlands where the covenant system of environmental regulation is based on voluntary agreements between industry, government, and environmental organisations (Allenby, 1999). In addition, research shows that self-regulation is effective when it is aimed at achieving public goals rather than self-serving objectives (Parker, 2002; Ayres and Braithwaite, 1992; Toffel and J. Short, 2011). According to these studies, self-regulation is most likely to occur under the following conditions:

1. When government regulators have sufficient capacity and resources to monitor compliance;
2. When government regulators refrain from using these resources to force companies to adopt self-regulatory measures;
3. When there exists a reasonable consensus among regulators and regulated entities about the norms or standards governing behaviour, but divergence on the methods of achieving compliance with these norms.

It is notable that despite the term 'self-regulation' suggesting minimal government intervention, the conditions still heavily depend on regulatory bodies. Governments need to provide stability and guidance, which raises questions about the time required and the challenges in ensuring safety and protecting society.

While self-regulation implies a certain type of 'freedom' of development and determination of one's own route, it is important to consider the potential risks associated with this 'freedom'. In addition to the potential benefits of self-regulation, there are also risks related to safety and the protection of society. The failure of corporate self-regulation has been identified by regulators and politicians as a significant contributing factor to the worst environmental and financial disasters of the last century (Jodi L. Short, 2013b). An example of a disaster for which self-regulation can be held responsible is the explosion on a British offshore drilling rig that resulted in many deaths. In this instance, while self-development and exploration were widely applied, safety concerns were not adequately addressed due to permits that were not correctly in place and followed, leading to a disastrous outcome (Gold and Power, 2010).

Although self-regulation implies freedom, the other side of the perspective is related to a more controlled environment. In such an environment, strict regulations are applied that have a direct effect on developments by steering them. Strict regulation is predominantly concerned with safety and the protection of society by steering developments and ensuring they occur in a safe manner. However, these controlled environments may not always provide optimal support for accelerating the developments that need to be made. The perspective of self-regulation and having a controlled environment can be visualised and expressed in the following Figure 2.2.

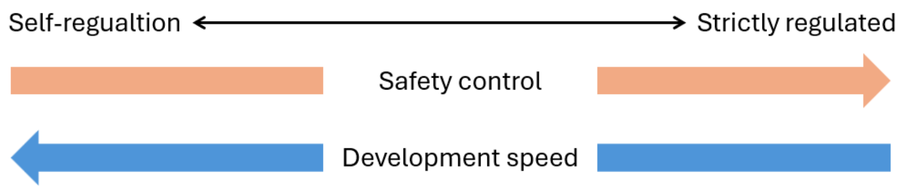

Figure 2.2: Self-regulation versus a strictly regulated structure based on safety and development speed (made by author).

Related to this self-regulation principle, Wynne (Wynne, 1988) describes in his paper, related to solving regulatory voids and self-regulation is the 'normal abnormality'. Only the moments when outsiders may catch a glimpse of the less orderly, less rule-controlled world of technology are when accidents and their after-effects happen. Because predominantly things that go wrong are seen, the belief is consolidated that normal practices are thus more orderly. Only until the point that something goes wrong, the newly developed technology is received, till that point the development can just continue. Secondly, according to Wynne, technology is not only about universality, it is about function in concrete and complex situations (Wynne, 1988). The key task of engineers and experts is to contextualize ideas or designs into working solutions. It is key to find a practical balance between contextualization and universality. Technology should be viewed as a form of large-scale social experimentation rather than a fixed, rule-bound system, acknowledging the inherent uncertainties and the need for an adaptive, ad-hoc rule-making process. Meaningful interaction between the public and experts, such as technology developers, is essential to gain a deeper understanding of the nature of technological systems and the complexities of their real-world applications.

To successfully regulate technological innovation, it is crucial to address the appearance of regulatory voids. Various studies highlight the need for clear guidance in this transition to ensure effective progress. Furthermore, governments must maintain a comprehensive understanding of technological advancements to maintain the ability to steer the process in the right direction. It is debatable whether there is already insufficient oversight, and whether regulatory bodies possess adequate knowledge of emerging technologies. This is evident in the current and future challenges associated with the pacing problem. To address regulatory gaps, there are two main approaches: allowing the market to undertake self-regulation or imposing strict regulations that must be followed: strict regulation and not loose control. The latter may result in a slower but more controlled environment. However, it is essential to maintain an optimal pace for innovations and technical developments. The establishment of regulatory frameworks that provide clear guidance, while simultaneously addressing the issue of regulatory voids, is essential for achieving this objective. The following section will elaborate on the various ways to set up regulatory frameworks to prevent the occurrence of regulatory voids.

2. Regulators and addressing regulatory voids:
Regulatory voids emerge when the development of new technologies cannot be adequately regulated. Often technologies outpace the regulatory capacity of the regulators (Wynne, 1988). Often regulators are governmental institutions or more general policy makers. In the context of transitions, regulatory voids can hinder investment, slow down innovation, and create an environment where market actors are uncertain about compliance requirements and long-term viability. The role of regulators is critical in addressing these voids. However, their role is not necessarily to actively drive technological development but rather to facilitate conditions that enable market-driven progress to allow technologies to be adopted. Regulators play a crucial role in addressing regulatory voids by setting clear legal and institutional frameworks that provide stability and predictability for emerging technologies. To prevent procrastination, they must offer interim guidelines and engage with stakeholders to reduce uncertainty (OECD, 2020). Facilitating public-private collaboration is essential to align industry efforts with national goals and foster innovation. Additionally, regulators should address information gaps and standardization issues by conducting risk assessments and promoting industry-wide technical standards.

3. Adaptive regulatory capacity throughout technology development:
The adaptive capacity of government regulation can be relevant to limit regulatory gaps or prevent them from opening up. However, it is not always easy to provide adaptive regulatory governance,

as developments need to be closely monitored in order to be able to evolve. Creating a balance between formal and informal (government) institutions that complement each other is desirable to create a more adaptive understanding (Pahl-Wostl, 2009). The essence of managing new technological developments is to deal with uncertainty and risk. Development is an ongoing process that does not have a readily known, fixed goal that can be regulated. During this process, society and other actors are exposed to potentially unsafe conditions if a developer has the ability to do whatever it takes. This is where the importance of regulation in terms of the need for protection comes into play. If governments are too protective, technological development may not proceed at the desired pace. The result is a stagnation in the pace of development and the need for precise regulatory development.
One way to address the regulatory gap is to closely monitor technological developments (Bennear and Wiener, 2019). However, it takes time to monitor this gap and technology will continue to evolve in the meantime. Knowing what is going to evolve allows better regulation to be developed. One way to see the regulatory development and the ability to narrow the regulatory gap is to constantly intervene and make a regulation that is getting stricter from time to time. This can continue until there is sufficient regulatory control and the gap no longer exists.

As simple as this sounds, it is much more difficult to implement such an adaptive method. It requires constant steering and monitoring, accurate prediction of development and constant monitoring of the potential risk to society. Two important aspects that must not be neglected are the scale of technological development and the development pressure. As the development affects many actors and industries, the amount of monitoring required is too large. The pressure also means that the development has to be fast, but the faster the development, the faster the regulation (OECD, 2024).

4. The role of subsidies for market adoption:
From a financial perspective, the role and effect of subsidies in determining whether or not a niche innovation is accepted by the regime is worthy of consideration. On the one hand, subsidies can facilitate the transition from the early stages of development to the later stages, where the innovation will be adopted at the regime level. On the other hand, subsidies can also influence the continuation of the adoption, as they may influence the decision-making process of the regime. Government subsidies, largely derived from the landscape level, facilitate the transition of industrial clusters through the valley of death and potentially enhance the efficacy of scientific and technological achievements (Yin, Yan, and Zhan, 2022). It can be seen that government subsidies play a pivotal role in the innovation adoption stage, particularly in the case of high-innovative industrial clusters.
However, there is also a potential adverse effect of government subsidies. Due to the government agencies' attempts to influence the technology in a specific direction, investors may become concerned, which could impact the market's ability to sustain itself. If there is a perception that the market is driven by a technology push rather than a market pull, investors may be hesitant to invest (Murphy and Edwards, 2003). They may be unwilling to rely on subsidies, as more risks are needed to be taken and as a result, this could potentially lead to a situation where the market is only sustainable with the subsidy in place. Furthermore, the form of subsidies in tax credits, which are vulnerable to change and therefore provide an uncertain benefit to the entrepreneur and investor; will be particularly problematic if the market is heavily dependent on government subsidies that could be withdrawn before the conclusion of an investment (Murphy and Edwards, 2003).

2.2. Where regulatory voids emerge in technological innovation

In the previous section, the conceptual foundation of regulatory voids was explored, and a potential suitable definition of a regulatory void was provided. Additionally, the size and evolution (development pace) of these voids were examined, along with potential approaches to mitigate their impact. This section focuses on where regulatory voids are likely to develop and identifies the most critical stage in the context of the energy transition. To determine the key point at which these voids emerge, the technology development cycle is introduced, providing a framework that outlines the various stages through which technologies evolve over time (Foxon, 2005).

Before examining the technology development cycle in detail, it is important to recognise that regulatory voids can arise in two distinct forms, both linked to the failure to adequately address technological advancements. In general, when there is a lack of clarity regarding the technological aspects of a given regulation, a figurative gap (or the void) emerges. This gap can originate from two primary sources:

1. Technological advancement or the emergence of a novel concept has occurred, yet the implications for regulatory development remain unclear and thus regulated (Wynne, 1988).
2. The regulatory framework is undergoing modification (subsequent to change), which has resulted in the technology that is currently in use no longer being fully subject to regulation (Patterson, 2023).

While both scenarios are important to consider, the first is far more common and is therefore the primary focus of this research. A regulatory system that fails to align with and address an existing technology is an exceptional case rather than the norm. Consequently, this study will concentrate on technological innovations that lack clear regulatory oversight. As this research focuses on the first concept, development not able to adequately regulate, it will serve as the foundation for further analysis with regard to the technology development cycle (Foxon, 2005).

2.2.1. Technology development cycle

The technology development cycle is an approach that takes a technology idea or innovation from concept (knowledge) to commercial adoption of the innovation. The technology development cycle consists of several stages, starting with ideation and progressing to diffusion and adoption. Each stage of the model consists of several specific tasks, resources, expertise and (external) forces required. Figure 2.3 gives a representation of the model including external forces, followed by a detailed explanation of the model.

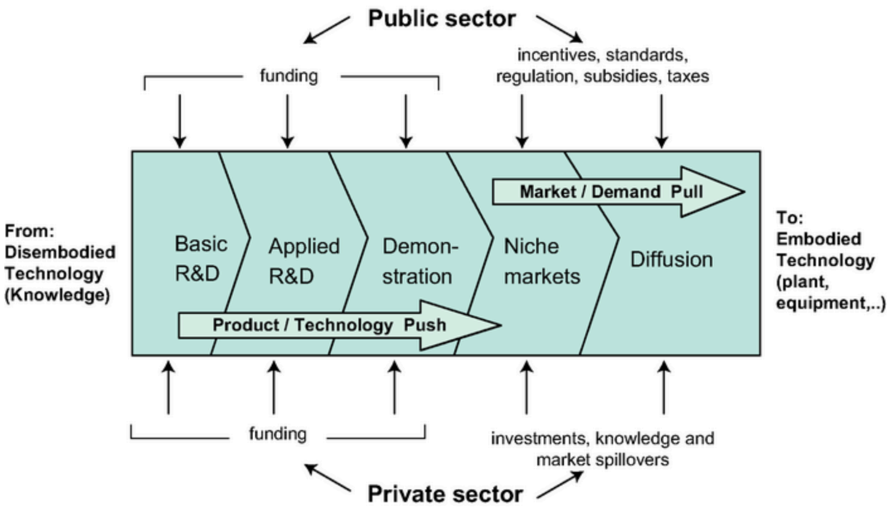

Figure 2.3: Technology development cycle including the main driving forces (Foxon, 2005; Grubb, 2004).

The model presents a logical progression, starting with an idea that evolves over time and is introduced to external factors such as the private and public sectors (Diaconu, 2011; Netz et al., 2007).
At each stage of the technology development cycle, the basis of LNG technology is introduced (Pierce Jr, 1982; Corbeau et al., 2016). LNG, or liquefied natural gas, is natural gas that has been cooled to a liquid state for storage and transport. This technology revolutionised the energy sector by enabling the efficient transport of natural gas across long distances. LNG has significant potential to reduce carbon emissions compared to traditional fossil fuels, especially in the shipping and heavy transport industries. After the explanation, a further understanding of the method is gained to clarify the different stages of the cycle.

- Basic R&D: This stage focuses on preliminary and fundamental research to explore new principles and/or technologies. Basic R&D involves theoretical and experimental research intending to gain more knowledge. Commercial objectives are not the focus at this stage, rather it is driven by curiosity. A disembodied stage means that technology exists as pure knowledge or discovery. Paths are paved and explored for further development, often supported by public funding and academic and knowledge institutions.

  Input: funding from the public and private sector and contributions from research institutions

Output: knowledge and scientific principles that can develop in a later stage to potential practical (technology) applications.

LNG case: The groundwork for LNG technology began with research into the liquefaction of gases in the early 20th century. Scientists worked to understand the thermodynamic processes required to cool natural gas to cryogenic temperatures. This basic research laid the foundation for the development of LNG storage and transport solutions.

- Applied R&D: the objective of this stage is to turn basic research fundamentals developed in the previous stage into practical applications. Most of the focus is on addressing real-world problems with specific technological solutions by implementing the basic R&D discoveries. The applied R&D stage is more product-oriented and has influence from both the public and private sectors. The raw knowledge is shaped into tangible technologies and creates functions products or systems that need to be tested and evaluated before moving to the next stage.

  Input: funding and knowledge from both the public and private sectors containing also research and development.
  Output: potential prototype, early-stage technologies, models or strategies that are ready to be demonstrated.

  LNG case: Researchers and engineers developed the first small-scale LNG plants and storage systems, allowing natural gas to be cooled, liquefied, and transported in specialised tanks. Early tests focused on making the process cost-effective and energy-efficient while ensuring safe handling of the cryogenic liquid.

- Demonstration: here the goal is to explore and make sure that the technology that is developed, works also in real-world conditions. Demonstrating reliability, feasibility, safety and effectiveness of the technology or strategy at a specific scale or in a specific market. Testing the development in the right environment is key before adapting further. This helps to identify the challenges or areas where improvements to the development need to be made. Bridging the gap thus between the R&D phase and applying it to the real world and the markets. In addition, it is key to gain buy-in from investors and regulatory bodies, providing and showing that the technology that is developed has practical applications.

  Input: investments from the private and public sectors, making the development more tangible and finding support for large-scale testing and feedback from the market.
  Output: pilot projects, identification of interest market parties, testing regulations and the wider application and implementation of the development.

  LNG case: Demonstration projects included the construction of prototype LNG storage and re-gasification terminals. These facilities allowed for testing the transport of LNG from production sites to terminals, where it was converted back into gas for use in power generation and industry. Such projects demonstrated the feasibility of integrating LNG into existing energy infrastructures.

- Niche markets: the demonstrated technology is brought to market. This may be in a specialised or limited market segment. The markets can be considered relatively small, as this is where new technologies were adopted earlier. The technology itself does not have to be fully mature and operational or the most cost-effective to be adopted. The niche market environment can be seen as a place where new technologies can develop with market pressures and constraints to further develop and demonstrate. This may result in the most cost-effective and safe development for the market.

  Input: Investments from the market into the newly developing technologies and niche market requirements for the technology to develop.
  Output: technology begins to form towards the market and will develop according to the wishes of the market. The start is made for a broader diffusion of the technology.

  LNG case: The initial adoption of LNG occurred in niche markets such as marine transport and off-grid energy supply. Shipping companies began using LNG as a cleaner fuel alternative, driven by stricter emissions regulations. Early adopters also included remote industrial operations that relied on LNG for reliable energy supplies.

- Diffusion: in this stage the technology transitions from a niche market orientation towards the mainstream markets, it becomes a well-known or standard solution that is relevant to add to the market. It can fit in the current market or can replace parts of the market. The diffusion refers to the widespread adoption of the technology across a larger market. Due to the cost-effective improvements that are made the technology becomes more widely accepted and can improve due to the 'economies of scale'. Regulatory frameworks, including among other incentives, standards, regulations, subsidies and taxes, can help accelerate the process of development.

  Input: mass or high market demand. Further investments from the private sector and from the public sector regulatory support to help accelerate the new development.
  Output: the technology is widely adopted in the market and becomes embedded in the wider socio-technical system. It contributes to the creation of "embodied" technology in the form of equipment, plants and systems.

  LNG case: LNG technology diffused rapidly in the global energy market, becoming a key component in the diversification of energy sources. Major ports and energy hubs developed LNG terminals, and their use in the transport sector expanded. Public and private investments, along with supportive regulatory frameworks, helped LNG achieve mainstream adoption. This transition highlighted its potential to reduce greenhouse gas emissions and provide energy security.

The technology development cycle is a model that can be considered for various developments related to technology. It provides a logical framework for understanding the different stages of a technology development process. It should be noted that technologies can be introduced in a variety of ways, including by skipping some stages or following an alternative path that deviates from the conventional 'normal' trajectory. The following Section 2.2.4, 'Defining Regulatory Steering Type', will delve deeper into the regulatory developments from the public sector.

2.2.2. The occurrence of regulatory voids

Section 2.1 provides the definition of a regulatory void within the conceptual foundation (definition regulatory void: 2.1). The regulatory void arises from a certain degree of misunderstanding or misinterpretation of the technology development in question. The regulatory institution (regulator), often a specific level or type of government, struggles to effectively guide and facilitate technological advancement, either by ensuring its progression or enabling its adaptation to the market. Furthermore, it has been postulated that the size of the regulatory void can evolve over time. When there is a considerable absence of accurate regulatory guidance, the divergence between the actions of the government and those of the technology developer can increase, resulting in a lack of clarity regarding the technology in question. To address the regulatory voids, it is thus important to find out where they occur in the technology development cycle.

There are two critical points in the technology development cycle where regulatory gaps can emerge. The first is obvious: this is where the R&D takes place. This is where the new technology being developed may not comply with the current regulations in place at the time of development (Lescrauwaet et al., 2022). The second place in the technology development cycle where regulatory gaps can arise is in the diffusion stage. In this stage, the technology needs to be adopted in the existing market where current regulations are in place. This adoption takes time because the regulations need to be changed to accommodate the technology being developed, and making these changes takes time.

An explanation of regulatory gaps in both the R&D and diffusion stages will be explored and explained in the following section. This is joined by a deep dive into the regulatory gaps that occur in the diffusion stage, focusing more on the aspect of avoiding slowing down the technology adoption process.

Regulatory voids in the R&D stage:
During the research and development phase, innovators and researchers often work on technologies that do not fit within existing regulatory frameworks. At the early stages of the technology development

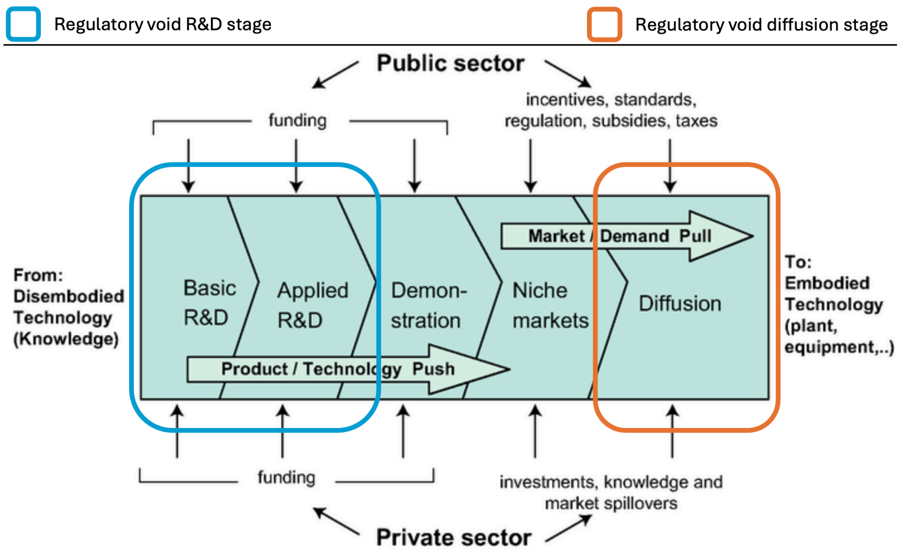

Figure 2.4: Technology development cycle with indicated places where regulatory voids will appear (Foxon, 2005; Grubb, 2004).

cycle, regulations are typically designed around the current market structure and may not accommodate emerging technologies. This misalignment is expected, as new developments are still in their infancy. Additionally, technological progress frequently outpaces the ability of government bodies to provide timely regulatory guidance, ultimately leading to the emergence of regulatory voids.
However, it is essential that innovation continues while remaining within boundaries that safeguard society. Public safety is a critical concern, particularly for the public sector, which plays an ambiguous role in this context. On one hand, it must foster technological development; on the other, it must ensure that such advancements do not negatively impact society (Borins, 2001). Technological innovation has historically been a major driver of economic growth, meaning that restricting technological progress is not desirable. Nevertheless, the lack of clear regulatory guidance for emerging technologies often causes innovators and researchers to hesitate when investing in their development.
One way to encourage innovation while maintaining oversight is through controlled regulatory environments, also known as regulatory sandboxes (Fenwick, Kaal, and Vermeulen, 2016). These frameworks allow developers to explore and test new technologies under the supervision of regulators. By offering greater flexibility, regulatory sandboxes provide developers with the freedom to experiment within a structured environment. This flexibility can take different forms, such as temporary exemptions from certain regulatory requirements or financial incentives, such as subsidies for innovation. However, regardless of the degree of flexibility provided, strict regulatory oversight remains essential to ensure accountability and mitigate risks associated with emerging technologies.

Regulatory voids in the diffusion stage:
The second instance of regulatory voids occurs during the diffusion stage, where the technology must be adopted by the market. For a new technology to be successfully integrated, it must comply with existing regulations. However, when regulations are outdated or incompatible with the innovation, regulatory voids may emerge. In many cases, existing regulatory frameworks must be modified or updated to accommodate technological advancements; a process that can be time-consuming and significantly slow down adoption.
One major challenge is that regulatory systems are often deeply entrenched. Regulations are generally well-established, widely accepted, and tailored to support existing markets. As a result, adapting these frameworks to accommodate new technologies can be met with resistance, making widespread adoption increasingly difficult. Furthermore, incumbent stakeholders, those already dominant in the market, may resist innovation to protect their position, further slowing the adoption process.
Beyond national regulatory challenges, cross-border regulatory alignment presents an additional barrier to widespread technology adoption. While global cooperation has increased in recent years, significant differences in regulations still exist between jurisdictions, even within shared governance structures.

For example, within the European Union, Germany and the Netherlands operate under the same overarching regulatory framework but have taken distinctly different approaches to autonomous vehicle regulation. The Netherlands has adopted progressive policies, allocating testing zones to encourage the integration of autonomous cars into its mobility network. In contrast, Germany has imposed much stricter regulations, despite both countries being subject to EU law (Henkel et al., 2017). This illustrates the complexity of aligning regulations across borders, which remains a key challenge for emerging technologies seeking international market adoption.

2.2.3. The importance of addressing regulatory voids in the diffusion stage

This research focuses specifically on preventing delays in the adoption of technological developments, understanding and addressing regulatory voids in the diffusion stage is therefore crucial. Unlike earlier stages of the technology development cycle, where a technology is still being tested and refined, the diffusion stage marks the (final) point at which a technology is fully developed, validated, and ready for market adoption. At this stage, all technical, functional, and operational requirements have been met, meaning the innovation is capable of delivering its intended benefits, but due to regulatory gaps or uncertainties, it fails to be integrated into the market.

This lack of adoption is particularly problematic in the context of the energy transition, where technological innovations are urgently needed to support the shift towards more sustainable energy systems. If regulatory frameworks are not in place to facilitate the uptake of proven technologies, their potential impact is effectively delayed or even entirely lost (Majone, 1997); the consequences of this are twofold:

1. Missed opportunities for sustainability gains: technologies that could contribute to decarbonisation, energy efficiency, or grid stability remain unused, slowing progress towards energy transition goals.
2. Inertia and investment hesitation: uncertainty surrounding regulatory approval or market access discourages investment, making it less likely that companies will scale up production or further improve the technology (due to lack of implementation).

This research, therefore, places particular emphasis on how regulatory voids at the diffusion stage act as a barrier to market adoption, despite a technology having already completed all prior stages of development. This study aims to highlight policy gaps that need to be addressed to ensure technological developments for the energy transition are not wasted due to outdated or absent adequate regulations to stimulate market adoption. The next section will provide a more detailed exploration of the definition of regulatory voids in the diffusion stage, including the principles of the economies of scale and how the institutional theory can be used to adequately address voids in the diffusion stage.

2.2.4. Defining regulatory steering type

Before exploring potential strategies to address and overcome regulatory voids, it is important to first examine the important characteristics that determine the most appropriate approaches. Several factors influence the development of a regulatory framework for technological advancements. The following aspects will outline the need for specific types of regulatory steering and inform the potential strategies discussed in the next section, particularly in relation to technology developments at the diffusion stage.

Nature of the development:
The nature of technological development plays a crucial role in determining the appropriate type of regulatory approach. Two primary types of transitions can be identified as key parameters:

- Radical developments: these require robust and transformative regulatory frameworks (Geels, 2019). Although radical changes may appear to take place over a short period, they are typically the result of decades of restructuring. Given that such developments often reshape entire systems, they demand directive regulations to provide clear guidance and ensure a smooth transition.
- Incremental developments: these involve gradual system improvements, such as efficiency gains. Incremental changes require adaptive and flexible regulations that support continuous improvement without necessitating major structural shifts (Roggema, Vermeend, and Van den

Dobbelsteen, 2012). As they primarily enhance existing systems, their regulatory requirements do not always need to be long-term in focus.

Additionally, disruptive technologies can significantly impact ongoing transitions. These technologies often emerge unexpectedly, bringing unforeseen challenges that existing policies may not adequately address. Disruptive innovations require responsive regulatory frameworks that ensure they are integrated safely and effectively, while still supporting technological progress (Taeihagh, Ramesh, and Howlett, 2021).

Scope, scale of governance:
The scope and scale of governance play a crucial role in both technology development and the design of effective regulations. When regulatory guidance is provided for a specific aspect of technological development, it is essential to ensure that its scope remains focused and does not extend beyond the necessary limits. Regulatory requirements can exist at various governance levels, ranging from local authorities—where small government bodies collaborate with local stakeholders to provincial, national, European, or even global institutions. While local governments may face challenges in establishing clear regulatory direction, these challenges intensify as the regulatory scale increases (Jodi L Short, 2013a). To ensure that regulations are effective at all levels, it is crucial to consider a broad range of stakeholders, industries, and policymakers. As the scale of a technological transition, the number of involved parties increases, making alignment and coordination even more essential. Regulations must be both practical and enforceable across the entire system to facilitate smooth technological adoption (Oomen et al., 2018).
Governments at different levels play a central role in the implementation of regulatory frameworks, influencing both their effectiveness and scalability. However, cross-sectoral integration must not be overlooked, as regulatory policies often intersect with multiple industries and governance domains. Failing to account for interdisciplinary regulatory needs can result in policy silos, where regulations become fragmented and inefficient. Therefore, ensuring a harmonised regulatory approach across sectors is critical to facilitating technological progress and market adoption (Wiedemann and Ingold, 2022).

Role of stakeholders:
The role of stakeholders in technology development is of great importance, as regulatory frameworks alone are not sufficient to ensure the successful adoption of new technologies. While governments and policy bodies are responsible for designing and implementing regulations, their effectiveness ultimately depends on the willingness and capacity of businesses, civil society, and the public to engage with and adhere to these regulations. If key stakeholders are unable or unwilling to comply, the intended policy objectives may not be achieved, leading to delays in technological diffusion and market integration.
A participatory regulatory process is therefore essential to ensure that diverse stakeholder interests are considered and aligned (Smismans, 2016). Businesses, industry representatives, policymakers, consumers, and advocacy groups each have different perspectives, priorities, and concerns. Aligning these interests helps to create a balanced and effective regulatory framework that supports innovation while safeguarding broader societal and environmental goals. Early stakeholder engagement also helps to identify potential regulatory gaps and challenges before they become significant barriers to technology adoption.
One of the most critical dimensions of stakeholder involvement is the interaction between public and private actors (Hodge and Greve, 2007). Governments and regulatory bodies provide the legal and policy frameworks, while private-sector actors drive technological innovation and market implementation. A strong public-private collaboration can help bridge regulatory voids by ensuring that policies are both practical for implementation and supportive of long-term public objectives. In the diffusion stage of technology development, stakeholder engagement (particularly between the public and private sectors) becomes even more critical. At this point, technologies have completed the research, testing, and validation phases and are technically ready for market adoption. However, regulatory uncertainties, lack of financial incentives, resistance from incumbent industries, and misalignment with governance structures can hinder the widespread uptake of these innovations.
Ultimately, an inclusive and adaptive regulatory approach, built upon continuous stakeholder engagement and public-private collaboration, strengthens the effectiveness of regulations while fostering an environment that enables technological progress and smooth market integration (Smismans, 2016).

Safety and risks concerns:
It is of great importance that risks and safety are taken into account when developing regulations (Bounds et al., 2010). The period when technological development is active may be characterised by a high degree of uncertainty, which can present a significant challenge for innovating developers. The question is, whether the new technology that, the industry will invest a significant amount of capital in, will prove to be a viable long-term solution. Financial subsidies can provide reassurance and guidance when considering the potential financial risks associated with new technologies. However, such subsidies may also have their own set of advantages and disadvantages of course (Murphy and Edwards, 2003; Yin, Yan, and Zhan, 2022). Furthermore, the regulations must facilitate the development of safe innovations, protecting society from potentially dangerous developments that may harm. While this may appear to be a straightforward objective, the challenge lies in balancing the need for safety with the pursuit of novel solutions. When a technology is still in its development phase, it is essential to determine the appropriate set of regulations to support its safe and responsible development (Mendes et al., 2014).

Regulatory adaptability over time:
It is not uncommon for a technology to evolve over an extended period of time, during which the system in question may undergo significant adaptations to accommodate the new developments. Conversely, a new determining development may arise rapidly and can have a significant impact on the current situation. It is therefore crucial to ensure that regulations are designed with a certain adaptive capacity. Essential is that long-term regulations are designed in a way that allows them to accommodate the need for short-term actions. Including the capacity to adapt to create a stimulating environment that is aligned with the long-term future goals and potentials. The triple-loop learning process (Figure 2.5) is a concept that can be applied to this end. It is assumed that interactions in formal regulation and policy cycles are mainly restricted to single-loop learning, whereas informal learning processes are required to support double- and even triple-loop learning (Pahl-Wostl, 2009).

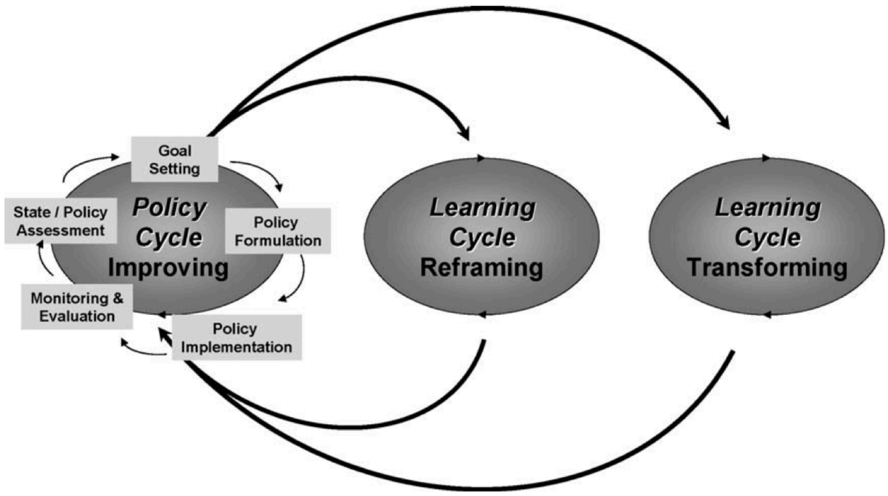

Figure 2.5: The triple-loop learning concept applied to government regimes (Pahl-Wostl, 2009).

The aforementioned aspects that define a set of regulations are related to the technical innovation that will happen or is happening. If these aspects are not fully comprehended, there is a possibility that regulatory voids will develop as a consequence of information asymmetry between the technical innovation and the understanding of this technical innovation that necessitates regulation. Consequently, as a greater proportion of the definition aspects of the regulations remain understood, the regulatory void that will emerge in the future will be more significant.

Effective regulatory steering is crucial for addressing regulatory voids, particularly at the diffusion stage of technology development. This sub-section has highlighted important factors influencing regulatory effectiveness, including the nature of technological change, governance scope, stakeholder engagement, risk management, and regulatory adaptability. Ensuring clear governance structures and strong public-private collaboration helps potentially bridge regulatory voids and facilitate market adoption. Additionally, balancing risk and safety considerations with innovation-friendly policies is essential. Without addressing these aspects, information asymmetries between technology and regulation will widen regulatory voids, delaying adoption. The next section will explore strategies to mitigate these voids in the diffusion stage; focusing on economic, regulatory, and institutional approaches to support effective technology integration.

2.3. Addressing regulatory voids in technology diffusion

The previous section outlined the key characteristics that shape regulatory steering, highlighting the factors that influence the development and implementation of effective regulations for emerging technologies. It became evident that regulatory voids often arise due to misalignment between technological advancements and governance structures, particularly at the diffusion stage, where technologies are ready for market adoption but face barriers due to regulatory uncertainty, lack of coordination, or outdated policies. Building on this foundation, the next section will focus specifically on regulatory voids within the diffusion stage, examining how these gaps emerge and what strategies can be employed to overcome them. Before exploring further how regulatory voids appear in the diffusion stage, it is a key aspect to define the diffusion stage.

Definition 3: *Technology diffusion stage*

The diffusion stage of the technology development cycle can be defined as the process through which technology spreads in the market and is adopted by market actors. This process is influenced by the actions of the public and private sectors, which may engage in collaboration or competition, and is shaped by regulatory developments (Kallio et al., 2016).

In the conceptual foundation (Section 2.1), a regulatory void was defined as a situation in which existing legislation and regulatory frameworks fail to adequately address or cover a specific issue, activity, or area, leading to ambiguity, uncertainty, or potential misuse (Wynne, 1988). While this broad definition applies to various stages of technological development, the nature of regulatory voids shifts as technology progresses through the development cycle.
At the diffusion stage, where technology has already undergone research, development, and initial validation, regulatory voids no longer stem from a lack of awareness or speed of regulation but rather from misalignment, rigidity, or fragmentation in existing governance structures. A regulatory void in the diffusion stage refers to a misalignment between existing regulatory frameworks and the technological, market, and societal conditions necessary for large-scale adoption. Unlike early-stage regulatory voids, which stem from an absence of regulation, diffusion-stage voids arise when existing regulations fail to accommodate, adapt to, or provide clarity for the integration of mature technologies into the market. This misalignment can result in legal uncertainty, investment hesitation, market entry barriers, and fragmented governance across different regulatory jurisdictions, ultimately delaying or obstructing the adoption of new technologies.

Definition 4: *Regulatory void in diffusion stage*

When existing regulations fail to align with the requirements of a mature technology. Rather than an absence of regulation, these voids arise from outdated, fragmented, misaligned, or inconsistent rules and standards; leading to uncertainty, market barriers, and delays in technology deployment.

2.3.1. Challenges in regulatory alignment during the diffusion stage

The ultimate goal of the diffusion stage is to get the technology development ready to become an embodied technology in the marketplace. The diffusion stage can be seen as one of the most difficult stages, as this is the moment when the development will break or make it and a lot has been invested. This stage can take a long time because it does not always involve public parties, private parties, society or a combination of these three and they must be on the same page for the development. Therefore, from the private sector, as shown in Figure 2.4, there are investments in money or knowledge but also market spillovers. From the public sector, incentives such as subsidies and regulations are provided to facilitate the diffusion phase and to help adopt the new technology development. Another role of the public sector is to protect society from any safety hazards and to make the developments acceptable.

The public sector is primarily responsible for developing rules and the allocation of supporting resources over the supply chain. These rules can be developed on different levels of governance. In the Netherlands, the following different levels of governance can be identified. Local government (municipalities) is responsible for local issues and spatial planning and must ensure that laws do not conflict with higher-level laws. The provincial government deals with regional issues and supervises the municipalities. The national government has primary responsibility for overarching issues of national relevance. Legislative power is shared between the government and the state general (parliament), while administrative power is exercised by central government authorities unless delegated to provinces or municipalities. As a member of the European Union (EU), the Netherlands must comply with its laws and regulations. In most cases, EU law takes precedence over national law, which means that national policies must be adapted. The Dutch government actively participates in negotiations at the EU level to shape policies that affect the country (Rekenkamer, 2023).

If the system is obtained from a higher type of governance to a lower type of governance and the different bodies adhere to each other, it seems like it is rather easy to implement and change regulations. However, this is easier said than done.

- Implementing regulations that actively support technological developments in reaching market adoption can be more challenging than merely adhering to directives from higher levels of government. One barrier to technological development is the widespread acceptance of legislation. It is not easy for the EU to make universally applicable laws. Even between European countries, there are significant differences that need to be overcome. Technological innovations and the structure of regulations vary from country to country. For example, Germany has a stricter regulatory approach to AI due to privacy concerns, while Estonia is much more focused on AI as a tool for innovation (Rijo, 2024).
- Newly developed rules and regulations must be accepted by society and industry. If the changes are too rigorous and too drastic, there may be resistance and this will slow down acceptance. Society also needs to understand why it is important that they are protected and that innovations do not develop as fast as some social groups would like. If we look at the development of AI, there are groups in society that want the new technology today rather than tomorrow, but there is also a group that is very hesitant about the new technology. This group, for example, has concerns about their private (Rijo, 2024). There are similar groups in society for industry.
- The current market is made up of different industries that work together in some way and cannot be changed easily. If the whole system is changed from one day to another, the market will fail and the established players will no longer have a position. It is also questionable whether the new players will be able to meet the needs of the market and how well the market will hold without the existence of the old market. A gradual transition from old to new will give more adoption possibilities but will cost much more time.
- A issue at hand that makes the diffusion stage hard for technologies to be adopted to the market is the distance of the public sector to the technology development. It is not always as clear what the innovation can bring to the market and how it should be regulated to make the adoption to the existing market possible from a public' perspective. Thereby there are most often multiple technologies that can be picked up at the same time but do differ from each other. In the first place, governments will try to stimulate by regulations that all of these developments have a chance to evolve, but at some point, decisions need to be made. Regulations and the type of regulations can stimulate this market adoption.
- The introduction of new regulatory measures is a challenging process. It is often difficult to determine the optimal approach, as the impact of regulation is not always straightforward to predict. Furthermore, the market may be negatively affected if parties develop methods to circumvent the new regulatory framework. Therefore, it is essential to ensure a gradual and measured approach to the implementation of new technology, to avoid disrupting the existing market.

The difficulties encountered in aligning technological advancement with regulatory frameworks have led to a widening gap between the two, which is likely to become increasingly challenging to bridge. This creates a growing regulatory void that becomes increasingly complex to resolve and makes the diffusion stage of high importance for development. To achieve this, it is essential to implement appropriate regulations and to gain a deeper understanding of the technology diffusion stage, in order to facilitate the desired progress.

2.3.2. Definition of different policy and regulatory types

Regulations and policies set by regulatory bodies guide developments or transitions, each with specific objectives, as shown in Figure 2.3. To enable change, they require support from different government bodies. Table 2.1 highlights key guiding and stimulating instruments, particularly the interconnection and the integral correlation between the various parties: public, private, society, and industry stakeholders.

Regulations:
A regulation is a certain rule that a person, company, or industry needs to adhere to. Regulations are made by institutions with authority. The definition can be seen in the following way: regulations are rules made by a government or other authority in order to control the way something is done in the way people/the industry behave (Collins, 2019). The goal is to control an activity or a process. Regulations can exist out of multiple rules. Especially the last part of Table 2.1 is related to regulatory steering: standards (a), permits (b), licenses (c), and sanctions (d). All have their specific goals and targets to help steer transitions in the right direction.

2.3.3. Economies of scale

An important aspect that is relevant for the diffusion stage, is the concept of economies of scale (George J Stigler, 1958a). In the development and adoption of technologies, financial considerations play an important role related to whether it is widely accepted or not. The economy of scale implies that when there is more produced, the price of the product will be lower, leading to the following definition that covers the core (George J Stigler, 1958a):

Definition 5: *Economies of scale*

To scale up the development process in order to reduce the price per unit, given that fixed costs will be distributed across a greater number of production units. The expansion of the economy will lead to an increase in the market size for the product or service.

A developing technology might be in line with the regulations that are in place and can be of great added value for society and the transition that is desired to be made, but due to the scalability issues and not being financially beneficial. If that is the case, the technology might not be widely adopted. To exemplify this, a further look can be taken into the widespread adoption of hydrogen fuel cells in cars (EU Science Hub, 2023). Vehicles, like cars, that use hydrogen do need a hydrogen fuel cell serving in some way as a battery to store electricity to power the electrical motor. A clean alternative is when hydrogen for the fuel cell is produced sustainably, compared to combustion engines. The fuel cell contains rare materials like platinum, which are costly and hard to source. This means the production costs of the hydrogen fuel cells will be high when they are not produced on a large scale. Complementary to this, the hydrogen infrastructure might not be well enough developed in order to make it attractive for car owners to switch to cars using hydrogen fuel cells. So high production costs and limited demand due to lack of available infrastructure result in the inability to scale up and use the method of economies of scale.
As also partially demonstrated in the previous example, the existing configuration of the market can be key for technology developments to be adopted. Solutions that are potentially beneficial for society can sometimes be hard to gain momentum due to external factors and dependencies. To get support for the innovation, public interventions are needed to create the potential for the economies of scale. Without these innovations, the market will stay the same due to the fact that the existing players can make a profit out of it and are not spending money on R&D to further innovate if not necessary.

Table 2.1: Overview of different types of regulations that can be implemented.

Regulation types:	**Interpretation and explanation:**
General policy:	A policy mandates, specifies or prohibits conduct in order to enhance a mission of a government/institution, ensure coordinated compliance with applicable laws and regulations, promote operational efficiency, and/or reduce risk (Wisconsin-Madison, 2022). It is a general written document that establishes a standard by which the government/institution manages its affairs. For the government, this may be for the general public or for industry.
(a) Standards:	Standards can be seen as formalised benchmarks that are established by governmental authorities, international bodies, or through consensus among various stakeholders. The main design goal for standards is to guide policy implementation and regulatory enforcement (Merriam-Webster, 2018). Standards serve as criteria to evaluate compliance with specific goals: safety, (environmental) protection, or for example ethical governance. Standards also relate to norms or what is considered to be 'normal'. In technical contexts, norms can refer to informal practices or accepted conventions that influence standards (Locher and Strässler, 2008). By aligning legal requirements with benchmarks, standards act as foundational tools for developing coherent (policy) measurements.
(b) Permit:	An official approval issued by a government body or other authorised institution that grants the legal right to undertake specific activities is referred to as a permit (Dictionary, 2024). Permits play a pivotal role in spatial planning and environmental policy development; ensuring that activities adhere to (statutory) regulations and also align with broader development plans and goals. Governments or private developers, for example, require permits for building and infrastructure projects to regulate urban development and enforce zoning laws. Operating and constructing without a valid permit constitutes a violation of the law or even termination of the project, underscoring the criticality of safeguarding (common) stakeholder interest and especially the protection of public interest. All in all, to ensure that he regulatory compliance (L. I. Institute, 2021).
(c) License:	Within the regulatory context, a license refers to a formal agreement or authorisation that grants an individual or entity the right to use, produce, or distribute certain resources or intellectual property (Doubleweb, 2021). A license may extend government control beyond a permit and can include private agreements such as those involving technology transfer or the use of patents. Licenses issued by governments are widely used in among others the energy sector; regulating access to scarce resources or ensuring compliance with sector-specific policies. Lastly, by establishing licensing frameworks, governments can balance innovation and public interest, particularly crucial in sensitive areas requiring direction and oversight (Kotabe, Sahay, and Aulakh, 1996).
(d) Sanctions:	Sanctions are mechanisms of enforcement employed by governments or regulatory bodies to ensure adherence to laws, regulations and policies. Sanctioning might involve penalties or restrictions such as fines, and operational and developing limitations on companies or stakeholders (School, 2024). Sanctions are in governance essential for maintaining accountability and addressing non-compliance. This can particularly be seen in the protection of the (public) environment where controlling can be hard. To illustrate, government bodies may impose sanctions on organisations that fail to meet the emission targets and thus in that way incentivise the compliance of the climate goals. Policymakers uphold through sanctions the integrity of the regulatory frameworks that are in place and determine and punish unlawful behaviour and activities.

2.3.4. Institutional theory

The regulation development has by studied by various scholars, among others Geels and Schot (2007) who refer to the institutional 'rules of the game' as a useful representation for understanding the socio-technical transitions and the technology diffusion. The institutional research tries to support also a more detailed analysis that goes beyond 'obtaining a view'. Obtaining aggregate explanations of alignments within and between the different parties leads to explanations of chains of events, and of particular events that happen at different scales (Huxley, Owen, and Chatterton, 2019).

The relationship of the institutional theory to other theories:

The institutional theory is an independent theoretical framework that is not directly related to other theories like strategic niche- (SNM), transition- (TM) or adaptive- (AM) management. The primary focus of the institutional theory is to create an understanding of how institutions shape and are shaped by human behaviour, organisations and social systems. Upon these parameters, rules, norms and cultural beliefs are formed.
While the institutional theory is independent, it incorporates various aspects of other management approaches. The institutional theory aligns with SNM on removing barriers to let innovations scale up to broader regimes, reflecting on path dependencies and institutional inertia. In addition, it helps to create legitimacy and stability for developments. TM align with the institutional theory of guiding technological innovations over decades and aligns with the evolution over time. Thereby different scales that are incorporated by TM help how institutions operate and influence behaviour at various scales (related to the technology development cycle). The institutional theory integrates the adaptive capacity from AM, which allows for adjustments to changes in a dynamic environment associated with transitions.

To use the more specific theory, an understanding can be used to gain a more detailed understanding with regards to the multi-level perspective's global analysis alignments (Geels, Kern, et al., 2016). The institutional theory is a viable theory that is used to make an analysis of this kind, the introduction of three pillars is used: regulative, normative, and cultural-cognitive processes (Scott, 1995). The institutional theory helps to understand the role and the function of the various regulations that can be in place. To further detail the process, the aforementioned pillars are defined in Figure 2.6. The quasi-evolutionary model analyses transition change as a function of two process types: shifting selection pressures and the adaptive capacity of actors. Shifting selection pressures include the acting upon regime actors to shape, but not determine action. These pressures can be directed, general or not directed. The adaptive capacity relates to the capacity of actors to respond to and shape selection pressures. It is a combination of the availability and coordination of resources to adapt to these selection pressures and shapes to form and direction of regime change over a longer period (Berkhout, Smith, and Stirling, 2004). Using this method results in the ability to explore the shaping power in a duality of selection pressures and adaptive capacity. To visualise the analytical process discussed, it is presented in Figure 2.6.

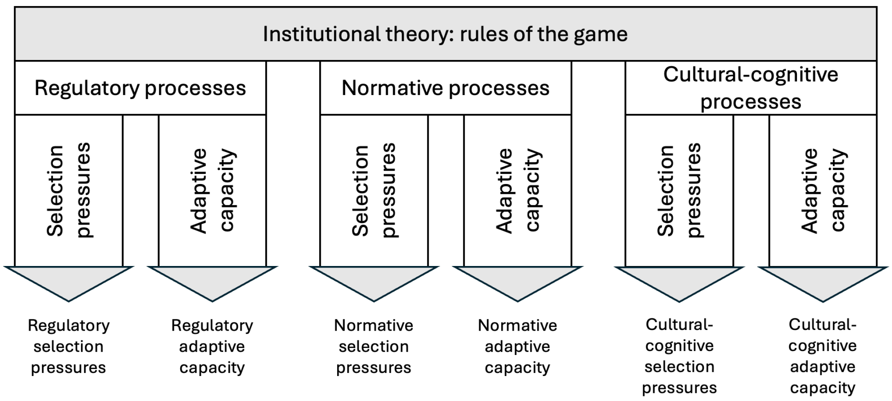

Figure 2.6: Institutional framework including process structures combined with the quasi-evolutionary approach (Huxley, Owen, and Chatterton, 2019; Scott, 1995).

Institutional theory (Scott, 1995) provides a framework that links both the interventions required to guide the development of the hydrogen infrastructure and links these interventions to the multilevel perspective when considering the level at which these actors are acting. The application of this approach helps to systematically categorise the different actions found in the case study and the interviews. The approach results in a suitable way to categorise the actions into six different boxes, based on three main pillars, based on the identified processes:

- **Regulatory processes:**
  The formation and the creation of rules, regulations and laws. These can be formal (enforced) rules to set out explicitly how things must be done. Predominantly these are imposed by the various levels of government or authoritative actors. The processes rely on legal mandates to shape behaviour and enforce compliance.
  - Regulatory selection pressure:
    Mostly selection pressures come from legal frameworks, compliance requirements and penalties. For example, this can be a carbon tax to incentivise actors to adapt to hydrogen technology for example. This pressures actors to adjust their practices in line with the new regulatory processes.
  - Regulatory adaptive capacity:
    The adaptive capacity is related to the act of how much an actor can adapt within the process, this is for example closely related to the ability to comply with the regulations or to innovate within the policy framework. Actors may develop hydrogen infrastructure for example in response to regulatory pressure by investing in new technologies.
- **Normative processes:**
  Relate to how things should be done by setting standards, providing guidance and identifying the best practice. This process is focused on acceptable, appropriate behaviour, and on shared values.
  - Normative selection pressure:
    These selection pressures arise from societal expectations, industry standards, and professional norms. As an example, increasing concern over climate change and sustainability development creates pressure on industries to make the transition to hydrogen. Benchmarks or best practices can be set by various actors to drive the expectations.
  - Normative adaptive capacity:
    The ability of actors to align with the evolving norms and values. Companies might adapt by branding themselves as leaders in sustainable practice, adopting hydrogen technologies to maintain the obtained reputation. Another aspect can be to adhere to the standards to remain competitive in the market.
- **Cultural-cognitive processes:**
  Shared beliefs, mental models and ways of thinking shape how individuals, organisations, actors and governments understand the world and their place within it. Generating the assumption about how things are done.
  - Cultural-cognitive selection pressure:
    Pressures like selection pressures from the beliefs and perceptions to adhere to the energy transition. As an example, the perception of hydrogen as a viable and clean energy source creates cognitive pressures on the industries. Shifting the collective understanding of the energy landscape can lead to increased hydrogen solutions by changing the culture and cognitive understanding.
  - Cultural-cognitive adaptive capacity:
    The ability of actors to embrace new technologies and ideas that are of common cultural understanding. Actors and policy developers may need to overcome deeply embedded assumptions about the dominance of transitional fossil fuels to be able to fully commit to the hydrogen infrastructure development. Investing in new research and exploring new options by changing long-term systems.

Each of these ’boxes’ represents a type of intervention with a clear definition of the processes it encompasses. This will provide insight into how the specific actions to be identified later relate to the actor in the socio-technical transition.

2.3.5. The role of institutional theory in addressing regulatory voids

The above-presented framework from the institutional theory offers an understanding of how organisations and actors can potentially regulatory voids. Regulatory voids, as redefined in 2.3, occur when technology is outpacing the regulatory capacity. Existing legislation and regulatory frameworks thus fail to adequately address specific issues, resulting in ambiguity and a process that is being slowed down. When regulations or legislation are absent or inadequate, the institutional theory highlights mechanisms that can guide behaviour and decision-making to fill these voids.

Shared understanding and (informal) norms:
Shared understanding and the importance of informal norms in the absence of present regulations are highlighted by the institutional theory. Institutions concerned with regulatory voids may rely on informal mechanisms to guide behaviour en establish expectations. To illustrate, industry actors might accept industry benchmarks that align with widely accepted values or norms. These types of instances that are relevant for the progress speed of technology development need to be adopted in formal regulations to provide guidance (Hardt, 2013).

Guiding principle: legitimacy:
A central concept in the institutional theory is legitimacy, playing an important role in adequately addressing regulatory voids (Jeong and Kim, 2019). Individuals and industry parties seek to obtain legitimacy by adhering to for example norms and actions that are normal and credible within the environment they are participating. Legitimacy can for example be obtained by innovation and living up to society's expectations. Formal legislation may not always cover adequately these expectations and technology innovations, thus encouraging actors to do self-regulation or collaborate to create quasi-regulatory frameworks that bridge gaps. In doing so, this can result in fractured innovation that is not fully supported by government guidance.

Collaboration and support:
Collaboration between industry parties themselves and/or the government can help to create a supportive structure that is needed to keep the development speed. A supported way to overcome regulatory voids by the institutional theory is to collaborate between various stakeholders. These collaboration efforts can be public-private partnerships, industry alliances, or multi-stakeholder forums. Initiatives like these enhance and protect the expertise and interests of multiple actors to develop suitable solutions that can potentially overcome the regulatory void. A second benefit is that this alignment and trust can foster support among the various stakeholder groups.

Trust and reputation:
Trust and reputation are of great importance for overcoming regulatory voids, as stability and guidance need to be provided (H.-K. Wang, Tseng, and Yen, 2014). Trusting the technology development and creating security will foster the implementation speed and market adoption. Reputation and trust can be gained through specific development efforts, as well as from previous or other market developments. In this context, the past can significantly impact mutual understanding and the commitment to developing technologies. Organisations and government bodies with strong reputations are seen as reliable, supportive, and credible, making them trustworthy in environments marked by regulatory voids. Having obtained trust and reputation may help to stimulate unpredictable decisions or insecure final investment (FID) decisions related to technology developments (Mishler and Rose, 2005).

2.3.6. Institutional theory related to the diffusion stage

The core processes of the institutional theory have been explored and these have their own individual characteristics within transitions. However, some of the processes are more relevant at certain points within the technology development cycle. As Angell (1995) and Scott (1995) describe institutions as "symbolic and behavioural (complex) systems that contain representational, constitutional and normative rules, that together with regulatory mechanisms define a common meaning system and give rise to distinctive actors and action routines". Scott describes that institutions are the deeper and more resilient aspects of social structure, a foundational bedrock for the societal structure that exists or is required, particularly during periods of technological transitions.

The rules of the game matter as much as the players themselves, meaning that the player as it is presented does make sense as much as playing to these rules accordingly. In addition to that, organisations are often driven by factors that are beyond just efficiency (Scott et al., 2005). Resulting sometimes in ambiguity, but in which the institutional theory could help give structure.

The processes of the institutional theory all have their own specific goal regarding the transition and creation of coherence. Accordingly, the result is that if all processes are followed they become rooted within the new system. However, for considering overcoming regulatory voids that appear predominantly in the diffusion stage of the technology development cycle, some institutional processes are more important compared to others.
When considering the technology development cycle and the regulatory voids that appear in the diffusion stage, the relation to more specific parts of the institutional theory can be made. In the adoption of developing technologies, the normative processes play a critical role during the diffusion stage. Here the adoption of technology spreads across organisations and industries supported by regulations from the government (Kincaid, 2004). The normative process involves professional standards, shared values, and expectations that influence how organisations, industries and parties in general behave and interact. Overcoming regulatory voids is important due to the fact that technology adoption is driven by industry professionalisation, industry norms, and the objective and will to align with industry (leading) leaders.

The normative nature of the process results in the criticality of the process (Scott, 1995). First, the normative process is crucial due to peer pressure and professional norms. During the diffusion, organisations do develop or do need to develop the feel to be compelled to adopt the technology as it becomes an industry standard. During the diffusion, this is an interesting aspect due to the fact that there can be multiple technologies ready for development and adoption. For a specific technology to become an industry standard, it is important that early adopters prove the value of the technology. In addition, institutions from various levels, experts, and professional associations play a key role in endorsing the technology by creating momentum and steering for the technology adoption.
Secondly, organisations tend to implement new technologies not just for technical benefits or return on investment, but also to appear legitimate and innovative. This helps position them among stakeholders, clients, society, regulators and investors that look out for the development and contribution of new technologies from organisations. Creating legitimacy through conformity is therefore essential in the diffusion stage for the adoption of new technologies.
Last, sharing knowledge and the creation of new knowledge is important to highlight the criticality of the normative processes from the institutional theory. The normative process encourages the sharing of information and experiences between various industry parties and organisations. Sharing this information must accelerate the diffusion and the uptake of technology developments by the market. This can be incentivised by training programs, fairs (industry forums), and workshops to help learn how to implement and optimise new technologies. An aspect that helps to learn and to set standards is self-regulation to demonstrate responsibility, gain legitimacy, and thus reduce uncertainty factors.

So, at the stage of technological diffusion, where predominantly regulatory voids are active, normative processes play a crucial role in facilitating adoption. Providing certainty, room for development, establishing standards, and fostering shared practices are essential for ensuring market security. These normative processes complement both regulative and cultural-cognitive processes, assisting industries and organisations in navigating uncertainties, bridging regulatory gaps, and shaping future regulations.

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3
Research Methodology

This chapter outlines the research methodology for the case study, interviews, and the development of findings concerning the emergence of regulatory voids within the hydrogen transition. The study combines theoretical insights with primary data gathered through a case study and interviews. A structured and systematic approach is essential to ensure that the findings are rigorous, well-substantiated, and contribute meaningfully to both academic discourse and practical applications.

To advance the analysis beyond the literature review, the primary data collection in this research starts with a single case study approach, focusing on the Hy3⁺ project to examine current regulatory challenges (HY3+, 2024). This case study consists of both desk research and observations from project meetings, enabling a comprehensive examination of hydrogen development with a particular focus on the Netherlands. As the project also involves Germany and Belgium, cross-border relations are considered as well. Additionally, primary data collection through semi-structured interviews ensures that diverse stakeholder perspectives; including governmental bodies, industry players, and experts. This section presents the selected stakeholder groups for interviews, along with the targeted number of interviews required to ensure the study's relevance and validity. Furthermore, observations at hydrogen fairs offer additional context, enhancing the applicability of the study by linking theoretical knowledge with industry developments.
While the first part of this chapter focuses on the case study and interviews, the final section outlines the methodology and analysis structure used. The research follows an abductive reasoning approach, iterating between theory and empirical findings to refine insights from the case study through the interviews. The Gioia methodology is applied to structure the qualitative analysis, systematically coding interview transcripts to identify patterns and overarching themes. This method supports a structured analysis by organising qualitative data into first order concepts and second order themes. Additionally, it allows for a systematic comparison of empirical findings with existing literature. By facilitating the identification of new patterns and insights, this approach contributes to the development of future scenarios for addressing regulatory voids.

3.1. Primary data collection: case study Hy3⁺

Within this research, the opportunity is there to conduct a case study focusses on an ongoing transition that is currently active: the adoption of hydrogen within the energy system. The case that will be studied is called Hy3⁺ (Arcadis and TNO, 2022) and focuses on the technical development of the hydrogen infrastructure between the Netherlands, Germany, and Belgium. This case study is currently being conducted by Arcadis on behalf of several stakeholders, including governmental organisations, producers and consumers of hydrogen, and developers of the necessary infrastructure. It is an independent study which considers the technical aspects of the implementation and adoption of hydrogen infrastructure.
The data collected in this study will help identify the obstacles hindering the development and adoption of the hydrogen network. Within the case study various bottlenecks are identified, these will include regulatory voids relevant to this research. By applying insights from the literature review to a real-world case study, these bottlenecks (particularly those linked to regulatory uncertainty and challenges) can be systematically analysed. This approach enables a wide understanding of the barriers to hydrogen network development and provides a structured basis for identifying potential solutions.

3.1.1. Case study methodology

A single case study is particularly relevant to gain a comprehensive understanding of the context, as it allows for an in-depth examination of potential challenges and opportunities, which is especially valuable in the context of hydrogen. While the literature review offers a broad understanding of regulatory voids and strategies to address them, a focused case study allows for a more in-depth examination of specific challenges and opportunities compared to a broader multiple-case study (Gustafsson, 2017). As hydrogen infrastructure development follows similar patterns to other large-scale projects, the findings of this study can be applied to a broader range of contexts. The case study combines desk research and observations to develop a thorough understanding of adequate developments while also playing a crucial role in structuring the subsequent interview phase.
This study follows an abductive reasoning approach, iteratively moving between empirical observations and theoretical frameworks to refine insights (Walton, 2014). Rather than merely confirming existing theories, the case study serves as a foundation for identifying key regulatory voids in hydrogen infrastructure development. Identifying gaps, inconsistencies, and challenges within the current regulatory framework, will provide a piece of essential foundational knowledge for conducting interviews with stakeholder groups. This ensures that interviews are guided by a well-defined understanding of regulatory barriers, allowing for a more targeted exploration of the issues at hand. The case study enhances the abductive reasoning approach by providing an initial foundation for identifying challenges, which then inform and shape the interviews. Insights gained from the interviews further refine and validate these challenges, allowing for an iterative process that strengthens the understanding of regulatory voids and their implications for hydrogen adoption.

Desk research Hy3$^+$ project:
Desk research will be conducted to gain an initial understanding of current developments and bottlenecks in the hydrogen transition. Before the Hy3$^+$ project, an earlier study, Hy3, explored the foundational aspects of hydrogen usage and integration. Building on these insights and findings, Hy3$^+$ was launched as a follow-up initiative to examine the practical implementation and adoption of hydrogen in greater depth. The desk study will primarily focus on the 2020 feasibility study (Arcadis and TNO, 2020), which provides key insights for identifying regulatory voids.

Observations during Hy3$^+$ sessions:
As an extension of the desk study, this research includes the opportunity to participate in the Hy3$^+$ project and attend relevant meetings. These meetings are both internal, involving the project-leading companies Arcadis and TNO, as well as broader sessions that include partner organisations. Appendix C provides an overview of the involved partner companies, while Table 5.1 lists the attended meetings during the case study. These collaborative sessions explore critical aspects of hydrogen network development, with a particular focus on identifying bottlenecks and regulatory voids.
Real-time project data, including insights not yet publicly available, will be utilised to deepen the understanding of implementation challenges. Observations play a key role in pinpointing the current obstacles within the regulatory framework and, ultimately, in defining the two regulatory voids examined in this research. A detailed introduction to the case study and the identified regulatory voids can be found in Chapter 4. Furthermore, Section 3.3.1 outlines the procedures for data storage and usage within this thesis.
To ensure ethical research practices and the use of information, consent will be requested before each meeting, and confidential information will be handled with care. Observations will be documented either by a designated note-taker or by the researcher. After each session, notes will be shared with participants for review and confirmation to maintain accuracy and reliability. This systematic approach to observations strengthens the abductive research process, ensuring that findings are well-supported by empirical insights.

3.1.2. The role of bottlenecks

Identifying bottlenecks is a crucial aspect of this study, making the Hy3$^+$ project particularly valuable. These bottlenecks that are identified by a wide range of stakeholder participants in the Hy3$^+$ project can include regulatory voids that are relevant to this research. By examining these bottlenecks, the study provides both a theoretical foundation and case-specific insights into the challenges currently faced in the hydrogen transition. By analysing the practical issues encountered in the Hy3$^+$ project, the study ensures relevance to real-world challenges in socio-technical transitions. This dual academic and practical applicability is essential for developing structured outcomes of this research. The goal is to establish foundational building blocks for future regulations, norms, and standards; providing insights that are both theoretically sound and practically implementable. Providing insights for both the academic and practical merit as identified in Section 1.2 research gap.

3.1.3. Observations at hydrogen fairs: creating general understanding

During this research, observations will be made during hydrogen fairs. These observations are not used as a primary data source but are used to create a general understanding of the current developments regarding hydrogen adoption.
Observations were made at three hydrogen fairs: the European Hydrogen Week, Vakbeurs Energie (Waterstof) and the Nationaal Waterstof congress. These events served as platforms for discussions and presentations by industry-leading parties, policymakers on both national and European levels, and researchers. The European Hydrogen Week was particularly interesting due to contributions from the EU experts outlining the emerging regulatory bottlenecks, regulatory frameworks and strategic priorities for the hydrogen transition. The macro-perspective offered a complementing understanding of the project-specific insights and perspectives obtained during the interview sessions. The Vakbeurs Energie offered a more bottom-up perspective through the eyes of local industries from the Netherlands regarding the use of hydrogen as an energy carrier or as storage. Table 3.1 presents an overview of the various hydrogen fairs.
In Chapter 6, the fairs give a second layer of proof and a more thorough understanding of the statements that were made related to overcoming the two identified regulatory voids in the case study. The observations from these events were utilised to contextualise findings derived from the interviews. Insights from both sources were cross-referenced to enhance their relevance and applicability to policy-making processes surrounding energy hubs. This approach, integrating interview data with observational insights, reinforced the robustness and depth of the findings. It provided a nuanced understanding of the interactions between stakeholder experiences and the broader policy environment governing hydrogen infrastructure development.

Table 3.1: Overview of visited hydrogen fairs.

Name of fair:	Location of fair	Date of fair:
Dutch Hydrogen Days	's Hertogenbosch (NL)	15/10/2024
European Hydrogen Week	Brussels (BE)	19/11/2024
Nationaal Waterstof Congres	Utrecht (NL)	04/12/2024

3.2. Primary data collection: interviews

Primary data collection plays a crucial role in this research and needs to be handled with care since not all data is already publicly available. The primary data source of this research is interviews that will be conducted among various stakeholders. In addition, data will be collected via observations in two ways. Via the participation within the Hy3^{+} case study and in addition by visiting hydrogen fairs. Each of these data collection methods has its added value and method which will be explained in this section.

3.2.1. Interviews and their role

As mentioned before, conducting interviews with various stakeholders related to the hydrogen transition plays a central role in this study. Qualitative interview data will be gathered via the methodology of performing in-depth semi-structured interviews, following the methodology outlined by (Kallio et al., 2016). Offering a structured approach will make sure all important questions are asked; but at the same time also the ability to be adaptive to the direction of the interview conversation.
The goal of the interviews is to be able to gather information from hydrogen-concerned players and experts who have experience with the hydrogen transition for at least a few years. Since the hydrogen transition is relatively new, multiple years of experience in the general energy transition is also credible for the interview. Key actors involved in the construction of the hydrogen infrastructure adoption include (semi-)government officials, hydrogen industry providers, hydrogen industry consumers, hydrogen industry producers, and hydrogen experts. Each group of stakeholders has a desired number of

interviews. The cumulative interview goal is to conduct between 11-17 interviews. In Table 3.2 the group of actors and the desired number of interviews is determined per group. Information saturation is the primary aim to achieve with the interviews, and while conducting more interviews would be ideal, 12 interviews are expected to be sufficient to ensure comprehensive data collection and saturation (Wormuth, 2022).

Table 3.2: Explanation of stakeholder groups and their corresponding targeted interviews.

Identified actor group:	Abbr.:	Explanation	#Interviews:
(Semi-)Government	sGov	Governments (ministries), government-related actors (Gasunie) and EU-level of government.	2 - 3
Hydrogen Producer	HP	Actors at the frontend of the supply chain responsible for the production of hydrogen (e.g.: building electrolysers).	2 - 3
Hydrogen industry provider	HiP	Involved actors that are providing (temporary) storage or transport options other then pipelines.	3 - 4
Hydrogen Consumer	HC	Back end of the supply chain that consumes hydrogen; e.g.: steel plants, chemical industries, and fertiliser production.	2 - 3
Expert	Exp	Academical or hydrogen transition experts that do not have an active role in the current hydrogen transition	1 - 2
Hydrogen Importer	HI	Companies that focus on the import of hydrogen; e.g.: the Port of Rotterdam or North Sea Port	1 - 2
Total number of interviews			**11 - 17**

Engaging these diverse stakeholders ensures a comprehensive analysis of regulatory voids by uncovering disconnects between policy and practice, as well as addressing gaps in safety, liability, and operational clarity. This approach captures the interconnectedness of the entire hydrogen value chain, considering the interdependencies among production, distribution, and consumption. By incorporating diverse perspectives, the analysis promotes the development of pragmatic, equitable, and stakeholder-aligned regulations. Additionally, input from experts and industry leaders fosters innovation and scalability, enabling forward-looking recommendations that support sustainable hydrogen adoption while addressing technical, operational, and societal dimensions.

This semi-structured interview approach offers a balancing and consistent framework with adaptability to the interviewee's background and expertise. The literature lens shapes the interview context and preliminary questions that are presented in the next section: interview protocol. The structure however remains flexible to adapt to respondents' answers, enabling nuanced insights. Semi-structured interviews allow for both comparability across interviews and the collection of specific knowledge from participants. While the natural flow of conversation facilitates detailed and authentic responses, the interviewer ensures all essential topics are addressed (Opdenakker, 2006; Adams, 2015).
The objective of the interview is to have a minimal length of 30 minutes, without introduction and closing. The storage and data handling of the interviews will be explained in detail in Section 3.3.1.

3.2.2. Interview protocol

An important backbone for the interviews and also to rely on during the interviews, is the protocol. The interview protocol can be found in Appendix B. The protocol is adjusted based on the stakeholders' role within the hydrogen transition. The middle part of the protocol introduces therefore specific oriented questions, while the introduction and closing are kept the same throughout the entire process. Appendix B only presents the English protocol, but when needed the protocol is also made available for the interviewee in Dutch.

Each interview starts in the same way, first, the consent form is discussed to make the interviewee aware of the dedicated usage of this interview. This consent form can be found in Appendix A. Thereafter, an introduction to this study is provided to explain among others the academic gap. Lastly,

before actually starting the interview, the interviewee is given time to give a proper introduction of their background and current work.
Questions and structure are changed based on the background of the interviewee. The goal of altering this semi-structured interview is to gain a more in-depth understanding of the interviewees' vision. After the introduction is completed the first part interview (as described in the interview protocol: Appendix: B) explores whether the interviewee's perspectives on hydrogen development and adoption align with the insights gained from the $Hy3^+$ case study and accompanying observations. The primary objective of this section is to validate key findings related to regulatory voids and broader challenges in the hydrogen transition.
The second part of the interview focuses on identifying strategies and approaches to effectively address these regulatory voids. This includes exploring how stakeholders independently perceive and navigate regulatory voids, as well as the processes and frameworks they believe should be implemented to support the development of hydrogen infrastructure.
The final part of the interview takes a forward-looking perspective, examining future needs, strategic directions, and overarching visions for achieving the hydrogen transition goals set by regulators and governments. This section aims to capture insights on long-term policy development, industry collaboration, and the evolving role of regulation in enabling a sustainable hydrogen economy.
These questions are formulated based on insights from the literature review and the $Hy3^+$ case study. The case study, along with the observations made, offers a clear understanding of the current bottlenecks and challenges. Meanwhile, the literature review provides a holistic perspective on the potential approaches to effectively address regulatory gaps.

3.3. Analysis methodology and data management

As outlined in the prior sections, primary data is collected through interviews with stakeholders and observations during the $Hy3^+$ case study. This data is systematically processed to address the main research question as well as the second and third sub-questions.

3.3.1. Data handling and management

This research makes use of primary data obtained via interviews and observations from predominantly the $Hy3^+$ case study. To deal with sensitive data, a data management plan (DMP) was developed and can be found in Appendix A.1. The plan was checked and approved prior to the start of the primary data gathering by the Technical University of Delft Management Support Staff. The DMP explains the types of data involved in this study and how these data will be handled. This includes how data will be stored and when transcripts of interviews will be protected and deleted. To protect the participants and to stimulate openness and transparency, (company) names are not mentioned in this thesis. References are thus made to the playing field in which the interviewee is active meaning that one of the stakeholder groups is mentioned.

In addition to the DMP, two important steps need to be highlighted regarding the consent form and the permission for recording. Before the start of the interview, the consent form is discussed to make the interviewee aware of the use of the later provided information. This consent addresses the potential risks of the interview, the publication information and how data is made anonymously. In some instances, the interviewees find it hard to fill in the form as presented in Appendix A.2 or want to make comments on the consent form. To facilitate this, the recording will be started and the consent form will be discussed. In this way, the consent form is signed within the meeting and recorded to prove understanding and the use of the data.
Each interviewee is asked if they agree to be recorded. The recording is made and saved on the TU Delft OneDrive. Afterwards, the interview is transcribed and anonymised. Personal comments are added to the transcript. This transcript is sent to the interviewee to provide the option to validate answers and statements. In some cases, a summary is presented to the interviewee. Once the interviewee agrees, the transcript can be used for data analysis.

To verify the quality of the data management plan, the entire plan is submitted to the Human Research Ethics Committee of the Delft University of Technology. Approval by this department and the DMP can be found in Appendix A.2.

3.3.2. Overview data collection methods

This research is concerned with different data types that all characterise the qualitative approach. From desk study and observations made during the participation in the case study, the regulatory voids will be determined. These identified regulatory voids form the basis and primary objective of finding answers from the interviews. These are taken into account when constructing the interview protocol. This protocol is made specific for the stakeholder groups that are obtained to be interviewed. An overview of the data types and the way of collection:

- **Literature Review:** the literature review contributes to the research by providing theoretical knowledge and setting the lens through which the primary data will be obtained. It incorporates findings from existing literature, reviewing government regulatory changes and the progress of hydrogen infrastructure development. The aim of the review is to gain an understanding of the transition and to provide a method for analysing the data.
  Collection method: systematic searches will be used to identify and locate relevant literature. The literature found will be categorised by topic to provide a logical understanding and a sound theoretical basis for the research.
- **Observations case study:** this phase of the research will be conducted as part of the case study, using an abductive reasoning approach to iteratively refine the identified regulatory voids. These regulatory voids will then be explored further during interviews, allowing for a dynamic interaction between empirical observations from the case study and insights from the interviews, thereby improving the depth and validity of this research.
  Collection method: the bottlenecks will come from the observations of the $Hy3^+$ study. During this session, the focus will be on the bottlenecks as the aim of the study is to identify them. The information will be categorised based on the bottlenecks identified.
- **Observations fairs:** notes from industry fair attendance provide valuable insights into interactions related to hydrogen infrastructure development. While these fairs (see Table 3.1) offer a broad overview of ongoing developments, they are not used as formal data sources. Instead, these observations serve just to enhance the researcher's general understanding of the hydrogen transition.
  Collection method: attending fairs, monitoring of new articles and visits to (public) speakers (debates) related to hydrogen infrastructure development. Detailed notes will be taken during these various events, and where possible these notes will be related to people.
- **Interview transcripts:** the transcript of the interviews will serve as the primary source of information. Where necessary, (parts of) these interviews will be anonymous to protect the interviewee. The transcripts of the interviews will provide detailed narratives, perspectives, visions and experiences of past developments. By interviewing a diverse group of stakeholders, a holistic understanding will be gained.
  The questions can be divided into three different parts, as shown in Appendix B. The first part tries to understand the type of actor the interviewee is. The second part focuses on gaining the interviewee's perspective on the bottlenecks identified in the $Hy3^+$ case study.
  Collection Method: to properly store and handle the data from these participants, guidelines based on the objectives will provide structure. The interviews will be recorded and thereafter transcribed.

3.3.3. Analysing interviews: Gioia methodology

A crucial step before presenting the findings, discussion, and conclusion is the analysis of the interviews. This section outlines the approach taken to ensure a well-established analytical foundation. The Gioia methodology is used as the primary analytical framework tool (Gioia, Corley, and Hamilton, 2013), offering a structured and rigorous approach to uncovering nuanced insights. This method creates transparency and credibility throughout the analytical process while allowing for theoretical abstraction needed in the discussion.

Once interviews are conducted, they are transcribed as soon as possible using Microsoft Word's transcription tool (Linda, 2024). After transcription, sensitive data is carefully filtered and removed where necessary to ensure compliance with ethical research practices. To maintain accuracy, interview transcriptions are shared with interviewees for validation. If the transcription is too extensive for full

review, a summary of key discussion points is provided instead. Once validated, the final transcriptions are uploaded to Atlas.ti, a qualitative analysis tool that facilitates pattern recognition and relationship mapping through systematic coding (ATLAS.ti, 2025).
The Gioia methodology follows an iterative process, enabling continuous refinement of insights as data is collected and analysed Gioia, Corley, and Hamilton, 2013. The main objective is to interpret the findings from the perspective of the interviewees by developing first order concepts (directly derived from interview responses) and second order themes (broader patterns that emerge from the data). These categories are then compared and linked to the literature study to identify similarities, differences, and their relevance in addressing regulatory voids. The Gioia methodology consists of three key steps, progressively shifting the focus to uncover patterns and develop findings:

1. **First order terms:**
   The individual transcript of the interviewee is central to the first step of the analysis. First order terms are assigned to parts of the transcript to describe the content without forcing any interpretations. These terms can be descriptive (e.g., 'technical', 'local', 'standards') or express underlying sentiments (e.g., 'emotional', 'frustrated', 'convincing'). The same terms can appear multiple times within or across transcripts, allowing for integral connections that will emerge.
2. **Second order terms/themes:**
   The goal of these terms also referred to as second order themes, cluster related first order concepts into broader, theoretical themes. Here the researcher starts interpreting the meaning behind the statements with the final goal of looking for patterns and relationships between the first order concepts and the various transcripts from the interviewees.
3. **Findings and interpretations:**
   The final step in the Gioia methodology is to combine second order themes into overarching aggregate dimensions. These high-level concepts form the foundation of the theoretical framework. While first order terms capture the interviewees' perspectives and second order themes identify patterns and relationships, aggregate dimensions provide a broader understanding of the phenomenon. This step moves beyond interpretation to create a structured explanation that contributes to theory development.

Thereafter, connections and comparisons with the obtained literature are established, ultimately contributing to the Discussion (Chapter 7). This ensures the balance between honouring the participants' voices and achieving the theoretical abstraction that is needed for this research. In this study, these step allows for connections to be drawn with the institutional theory, validating or expanding existing frameworks.
The iterative and flexible nature of the Gioia method makes it well-suited for complex qualitative research, particularly when exploring emerging or under-regulated topics. The methodology stays focused on real-world data, ensuring that theoretical insights are based on the actual findings. By first analysing and categorising the interview data before engaging with the literature, the approach maintains a structured yet adaptable path to theory development (Gioia, Corley, and Hamilton, 2013).

3.3.4. Coding collected interview data

Once all the interview data is collected, it will be qualitatively analysed according to the Gioia method. The analysis program is called Atlas.ti, a qualitative analysis tool that will help to identify patterns and finally identify the building blocks. The following steps need to be identified during the process to perform the analysis:

1. **Data import and coding:** The data obtained from the interviews will be imported into the programme. Here, the programme acts as a data manager. Once all the data is imported, coding will be conducted by highlighting and structuring parts of the interviews, preparing for the next step (Gioia methodology: first order terms).
2. **Data selection and categorisation:** After all relevant data has been selected, it will be categorised into groups, creating a structured framework (Gioia methodology: second order themes). This categorisation provides better insights into the important aspects and quotes by sorting them into appropriate categories. Relating the data to the structure of the research questions, particularly research questions 2 and 3, will offer a deeper and more holistic approach.

3. **Interpretation and findings:** Based on the various categorisations of the primary data, patterns and structures relevant to the regulatory voids can be identified (Gioia methodology: findings and interpretation step). The interpretation of the data is discussed in Chapter 7: Discussion, concerning the literature research, obtained primary data, and personal observations.
4. **Application to overcoming regulatory voids:** Based on the analysed data, interventions for the process regarding regulatory interventions will be proposed to address the regulatory voids. Here tangible building blocks for the process are identified based on the literature review, the $Hy3^{+}$ case study, and the primary data collection part. This will result in concluding and addressing the main research questions by linking the different data aspects considered during the thesis (Chapter 8).

Double layered analysis approach:
To analyse the interviews, a double-layered approach will be taken to gain understanding. First, a general understanding of the visions of the different stakeholder groups will be obtained. This will be done by coding the interpretation of quotes. This is done for all individual transcriptions and will result in an overview of how often visions are stated in the different quotes. In this way, the cumulative weight of certain quotes and visions can be identified. Thus, knowing how many stakeholders are interviewed per group, a more detailed overview is obtained as a first analysis step. The goal of these steps is to find patterns within the data that are interesting to further explore. To create patterns, and to make more comparisons, when needed the data will be normalised based on the number of interviews from the stakeholders.
Due to the creation of an understanding of the cumulative weight of the interviews, it is easier to gain an in-depth understanding. In the second step, a deeper dive is taken into more specific and relevant quotes from the different interviews. These relevant statements from different stakeholders will be analysed per category to test the relevance and connection to the institutional theory.

4 Case Study

The primary objective of this case study is to develop an understanding of emerging hydrogen technologies within the technology diffusion stage of the hydrogen transition. It aims to identify regulatory voids that will inform the interviews and contribute to a more precise analysis of the hydrogen transition. Ultimately, this case study seeks to partly answer the second sub-question of this research:

2. *What is the status quo of hydrogen infrastructure and market development?*

The first part of this section introduces the $Hy3^+$ project, providing a global overview along with the key stakeholders and organisations involved. This is followed by an analysis of the most significant bottlenecks that have emerged within the project and their implications for the adoption of hydrogen infrastructure. The bottlenecks serve as a foundation for pinpointing regulatory voids, which will be further examined in the interviews. By integrating case study findings with stakeholder perspectives, this approach reinforces the abductive reasoning approach, providing an iterative development of regulatory challenges and potential strategies to address these challenges.

4.1. $Hy3^+$ case introduction

Hydrogen technology has gained momentum over the past decades but continues to face challenges in transitioning from the diffusion stage to widespread market adoption. A key barrier is the lack of regulatory clarity and the complexity of establishing adequate regulations to support the integration of emerging hydrogen technologies. These gaps result in regulatory voids that must be addressed to facilitate progress and create development momentum. This exploratory case study focuses on the $Hy3^+$ project; a joint feasibility study conducted by Arcadis and TNO HY3+, 2024 and including many hydrogen industry partners. The study examines how both technical and regulatory bottlenecks within the hydrogen transition can potentially be addressed.
The $Hy3^+$ case study aims to identify the most critical regulatory voids that must be addressed to prevent further delays in hydrogen adoption. By examining these voids, related stakeholder groups are identified who can offer valuable insights into both the specific regulatory challenges and their broader context.

The project originates from the hydrogen transition underway in North-West Europe, driven by the shift from a fossil-based energy system to a more sustainable and intermittent energy infrastructure. The energy production of this system is mainly coming from solar and wind energy. This transition requires a stronger flexible energy system, one of the options to increase the flexibility is converting electricity from wind and solar into hydrogen (TenneT, 2024).
Exploring the relatively new concept of hydrogen presents a significant challenge for many stakeholders. Large organisations, such as Shell and the Port of Rotterdam, often face blind spots in development, leading to a certain bias. This bias stems from the shared ambition to transition towards a new energy system configuration, while simultaneously grappling with uncertainty—particularly concerning high-risk investment decisions. An additional challenge is the emergence of various sustainable alternatives, each requiring careful consideration. Competing options such as ammonia, high-voltage infrastructure, and CO2 storage add further complexity, making the decision-making process even more complicated.

For making complex and risky investment decisions, it is well worth for these types of industry companies to have performed an independent study, the Hy3^{+} case study can help create understanding and certainty between the involved parties. The initiated project looked at the aspect of producing hydrogen from offshore wind; however, the study resulted in the fact that there is not enough production capacity to fulfil the needs. Next to wind-produced hydrogen, the import of hydrogen became as a result increasingly important in order to create a potential concrete future supply chain.

The primary focus of the Hy3^{+} project is to conduct a feasibility study on the production, import, transport, and utilisation of green hydrogen. Additionally, the project assesses the technical capacities required to meet future hydrogen demands, evaluates the current status of infrastructure and regulations, and identifies the necessary steps to accelerate development in collaboration with industry stakeholders. For hydrogen production, the aim is to predominantly utilise offshore wind farms located in the Netherlands and Germany. In addition to domestic production, the project explores hydrogen imports, with (key) entry points being the ports of Rotterdam, Antwerp, Eemshaven and Amsterdam. The main demand centre for hydrogen considered in the Hy3^{+} study is the Ruhr region in Germany; with a focus on industrial applications as well as the use of hydrogen in the mobility sector.
The study concerns three main work packages that help examine individually how the hydrogen system can be implemented in Europe. Firstly the hydrogen demand is explored, thereafter the methods of transport and storage, and lastly the production of hydrogen from offshore wind. The overall goals of the Hy3^{+} study are the following:

- Analyse the feasibility of a transnational green hydrogen economy between the Netherlands, Germany and Belgium.
- Examine the potential of Green House Gas (GHG) reduction and increase the renewable energy deployment in the industry sector with a transnational green hydrogen economy.
- Examine potential business cases for the green hydrogen economy between Belgium, the Netherlands and Germany.
- Identify the implementation problems for green hydrogen implementation concerning transport, economy, production and usage.

The current analysis of the hydrogen network by Arcadis and TNO primarily focuses on the technical aspects of the hydrogen system. This includes evaluating key parameters such as pipeline diameters and projecting hydrogen import and demand for the coming years. Using available data and underlying assumptions, a model is developed to analyse different future scenarios, aligning them with milestones set by the European Union while considering the hydrogen capacities of the involved countries and industries. In addition to the technical assessment, the feasibility study also examines regulatory developments and societal needs, incorporating these elements into a PESTLE analysis to provide a comprehensive understanding of the broader implications of hydrogen infrastructure development (Christodoulou and Cullinane, 2019).

The progress of these meetings is internally discussed between Arcadis and TNO, focusing on the model results and the identification of bottlenecks. At specific intervals throughout the year, these discussions were also held with other parties involved in the project. These meetings provided an opportunity to present the findings of the Hy3^{+} study and gather feedback from the partners. An overview of the involved parties and their respective industries is provided in Appendix C. An overview of the type of parties, based on their type of industry/role, is presented in Table 4.1.

Table 4.1: Overview of actor types involved in the Hy3^{+} project.

Stakeholder:	Cumulative:
(Semi-)Government	3
Hydrogen Producer	2
Hydrogen industry Provider	3
Hydrogen Consumer	3
Academic expert/institute	2

To find the bottlenecks, the previous Hy3 report was closely studied to gain a certain basis (Arcadis and TNO, 2020). In addition, participation in the Hy3+ project is highly necessary and useful to gain a deep understanding of the rooted bottlenecks by doing observations. Leading ultimately to the identification of the regulatory voids. The total number and types of observations can be found in Chapter 5, specifically in Table 5.1.

4.2. Scenario development

The Hy3+ project consists of a technical network development part and an additional PESTLE analysis (Christodoulou and Cullinane, 2019). The technical development of the network involves setting input parameters to create a realistic network. This includes parameters such as weather factors, import location, storage possibilities, hydrogen production, and import and demand areas.
The following Figure 4.1 is an overview of the hydrogen network that is in place according to the German authorities, Belgium authorities, and Dutch authorities.

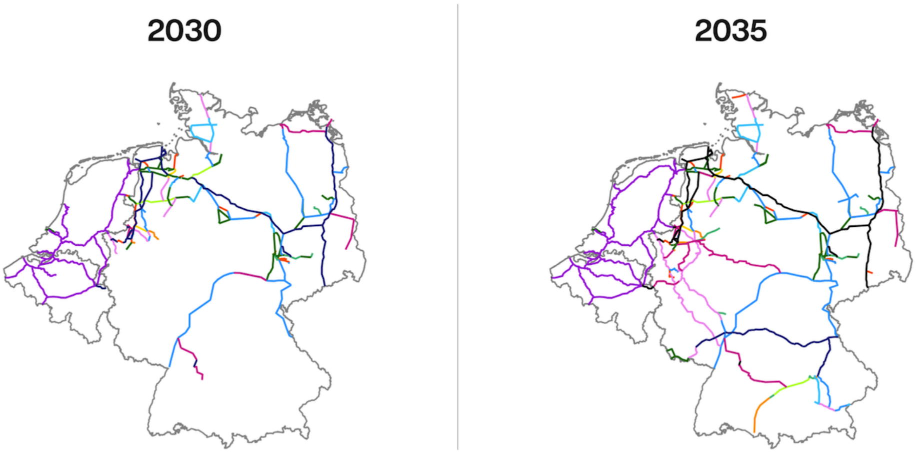

Figure 4.1: Left: hydrogen network development completion by 2030.
Right: hydrogen network development and completion by 2035 (HY3+, 2024).

European directives and regulations seek to stimulate and obligate the use of renewable fuels derived from non-biological sources (RFNBOs), thereby fostering the development and demand for these fuels, which is currently gaining momentum (RVO, 2025). It is anticipated that over the next decade, Germany's demand will exceed its combined domestic production and import targets. Given Germany's inadequate import and production capabilities and the geographical distribution of the country's major industrial clusters, the establishment of a transnational network is a logical and strategic decision. By linking Germany to Belgian and Dutch production or import capacities, the shortfall can be addressed, and a more robust and secure network can be formed, which will also benefit industrial players that require investment decisions in the next years.

4.3. Identification of main bottlenecks

Insights from the desk study and sessions revealed two bottlenecks that significantly hinder the implementation of hydrogen infrastructure. These bottlenecks, outlined in the following subsections, are particularly relevant for analysis as they highlight regulatory voids and the challenges in overcoming them. The identified bottlenecks involve multiple stakeholders with vested interests in the hydrogen network, all seeking assurances regarding the hydrogen development. However, there remains uncertainty about how regulations can be effectively designed to address these obstacles and facilitate progress.

4.3.1. In-completion of the network by 2030

Information from the Hy3+ project partners suggests that parts of the network will not be built. In particular, the section connecting the west side of the network to the east side of the network. This pipeline link is also referred to as the Delta Rhine Corridor (DRC).

Current plans do not include the DRC connection, which means that the western part of the Netherlands will not be connected to the eastern side of the network until 2032. Most of the hydrogen will be consumed in the Ruhr area of Germany. This is where large energy-consuming industries such as steel plants, the chemical industry and the fertiliser industry are located (Prologis, 2017). So, connecting to the eastern side of the network is a crucial part of making the whole supply chain work.
If the DRC is not built before 2030, there is a high risk that the Netherlands will miss out on early involvement in the hydrogen network. This means that investments in hydrogen infrastructure will most likely be made elsewhere. Take, for example, the hydrogen development for the port of Antwerp. In addition, the dependency and robustness of the network will suffer because the network will be less redundant. Finally, not being connected to the eastern part also means that the Dutch ports will operate in a so-called island mode (ClarkeEnergy, 2024). This isolation from the larger hydrogen infrastructure will mean that only the locally connected parts can benefit from the import, and this consumption is less than designed for. As a result, the hydrogen velocity of the network will be too high for some parts of the network. It can be concluded that the missing DRC will ultimately mean that the ports in the Netherlands will not be able to contribute to the development of the overall European hydrogen infrastructure in 2030.

4.3.2. Hydrogen market development

A second important aspect, which is of great importance for the acceptance of the existing hydrogen infrastructure, is the way in which hydrogen can be priced. Currently, there is a lot of uncertainty about how hydrogen should be priced and what that price should be. The uncertainty is mainly because there is not yet a real network of hydrogen producers, network operators and consumers. The hydrogen market is not yet established due to the fact that the front end of the supply chain is not connected to the back end of the supply chain. In order to determine the price of hydrogen, huge investments will have to be made in the development and construction of many industries. Consumers are also unsure whether they want hydrogen because of the price they will have to pay. Figure 4.2 is a simple diagram that shows the dependency of these elements.

A crucial factor influencing the acceptance of hydrogen infrastructure is its cost, particularly the final price paid by consuming industries. This price is often perceived as too high, given the risks and uncertainties associated with hydrogen adoption and market development. Currently, there is significant uncertainty surrounding both the method of pricing and the price level itself. This uncertainty arises primarily from the absence of an established hydrogen market, as there is no fully developed network connecting producers, network operators, and consumers. The lack of integration between the supply and demand sides of the hydrogen value chain further complicates market formation. Determining a viable hydrogen price requires substantial investments in the development and construction of supporting industries. Additionally, potential consumers remain hesitant due to uncertainty about future costs, impacting demand. Figure 4.2 provides a simplified overview of the interdependencies between these elements, illustrating how market development, infrastructure investment, and pricing uncertainty are closely interconnected.

Under normal conditions, the price of hydrogen (or any other product) is determined by the availability of the product and the level of demand for the product (supply and demand) (College, 2019).
In the situation of hydrogen deployment, there is an important aspect that needs to be taken into account when developing the market, which is infrastructure development. Without such an infrastructure, it is not possible to establish a market, which to a large extent determines the price. In addition, it is questionable who will develop such a network, most logically it will be the government. However, for the government to develop such a network, it must be sure that consumers are willing to use hydrogen in their industry. If this is not the case, the government is developing a credible infrastructure.

4.4. Regulatory voids in diffusion stage

In general, there is a lack of comprehensive technological understanding for the implementation of hydrogen infrastructure and the introduction of hydrogen into the system. Regulations related to transport, storage, market development and infrastructure development decisions are developing too slowly to meet the technological potential perspectives. Network aspects such as pressure and hydrogen purity are elements that are still awaiting final decisions, keeping consuming and production

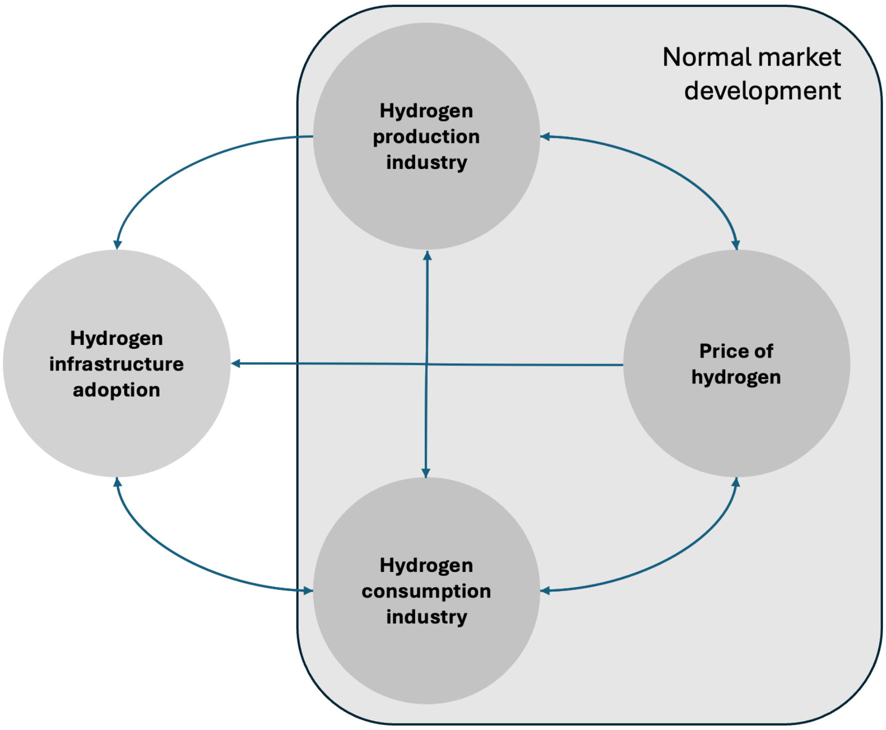

Figure 4.2: Dependency of different parts of the hydrogen infrastructure adoption (made by author).

industries waiting. In particular, regulatory bodies have not developed safety and operational standards that reflect the technological progress made. While the technical developments of hydrogen are gaining momentum and are ready for market introduction, the diffusion phase is being critically slowed down. Without the regulatory presence, the hydrogen process cannot be rewarded by the industries in terms of prioritisation based on emissions and financial prospects. The resulting regulatory gap discourages the adoption of clean energy carrier alternatives, slowing diffusion and deterring investment.
The occurrence of technology outpacing the regulatory development process, leading to the emergence of regulatory gaps, is also recognised by the Hy3$^+$ project. Within this project, two main issues pose problems in adequately addressing the gaps. Firstly, the creation of a well-established hydrogen market, which is essential to make financial investment decisions (FID) and to prevent a slowdown. There is uncertainty about how the infrastructure is to be developed. In particular, the moment of development shows delays and uncertainties that are not desirable regarding the feasibility of the energy system transformation goals. In the following subsections, these regulatory gaps will be celebrated.

4.4.1. Ambiguity around market design:

The regulatory gap is that the hydrogen market is not constructed like a normal market. There are still no concrete consumers, producers and suppliers who can determine the price of hydrogen and construct a real market. This uncertainty makes it difficult and hesitant for parties to move towards the use of hydrogen as an energy carrier. The challenge to overcome this regulatory gap is to create a situation where the market is regulated. For example, the gas market can provide valuable lessons for the development of a hydrogen market, although hydrogen has its unique characteristics. In Europe, the TTF is a centralised gas market hub with established pricing mechanisms based on the supply and demand of gas (TTF, 2024). Hydrogen does not have a hub like the TTF, which makes it difficult for stakeholders due to the lack of price transparency and liquidity. The industry is willing to develop but is reluctant because of the lack of a concrete market structure that needs to be facilitated at the national or European level. If there is a concrete hub that can regulate the market, the price mechanism will follow and industries will be able to make investment decisions. A possible method of subsidisation is an interesting regulatory aspect that needs to be considered. In this way, the consuming and producing industries can get a certain price for hydrogen, which is guaranteed by the European Commission.

Once this market mechanism is in place, parties that store hydrogen may also be able to enter the market.
Another way to kick-start the hydrogen market is to introduce a national or European CO2 tax (Emissieautoriteit, 2022). This tax could be used to encourage industries to become more environmentally friendly by producing less CO2. In the meantime, the money generated by this tax can be used to support the development of the hydrogen industry in many ways, such as creating a network or subsidising the price of hydrogen.

Void Market Development (MD):

The regulatory void in market development for hydrogen is characterised by the lack of a clearly defined and structured market framework. There is no established system for identifying (key) market participants (such as consumers, producers, and suppliers) and their roles within the hydrogen supply chain. This absence of these market structures leads to ambiguity about the responsibilities of different stakeholders, as well as uncertainties around market demand, supply, consumption, and the establishment of (long-term) contractual relationships. While technology developments in among others electrolysers are happening; the lack of regulations defining market parties how interact, how supply chains can develop, or how the risks are managed, results in hesitation among industries to invest in or adopt hydrogen as a viable energy carrier.

4.4.2. Inconsistency and information asymmetry in regulatory approaches and roll-out plans:

A major regulatory gap that slows down the process is the inconsistency of roll-out plans. It may be logical that this is the case on a European scale, as their plans have to be in line with each other, but on a national scale, this may not be so complex. However, there is still a national scale, and in the context of the Dutch hydrogen infrastructure plans, there is a lot of uncertainty about where to build. As mentioned earlier, an important part of the network that will connect the Netherlands to Germany will not be built in 2030 as previously planned but will be delayed by two to four years.

The Dutch national ideology describes hydrogen as an important aspect of the energy transition. The focus on the use of hydrogen at the national level is partly driven by the European targets that are being set. The way of implementation is still a concern, as other energy transport methods also have potential. High voltage networks can be built or the use of ammonia is a relevant energy transport method that is currently being considered. The existence of these alternatives makes the choice of hydrogen infrastructure quite difficult and results in a lack of regulations to stimulate implementation.

For the development of the DRC in particular, the biggest issue is regulatory approval and cooperation between the various (government-related) parties. Both TenneT and Gasunie are planning to work in the same trace, the so-called Delta Rhine Corridor. This is a corridor with an approximate width of 70 metres from east to west that is reserved for the laying of cables and pipelines in the Netherlands (Rijksdienst voor ondernemend Nederland, 10AD). The corridor will allow the transport of hydrogen, ammonia, CO2 and electricity (high voltage). Gasunie wants to build a hydrogen pipeline network, which means that the west of the Netherlands can import and transport hydrogen to the east of the Netherlands and connect to Germany. TenneT also wants to work in the Delta Rhine Corridor and wants to lay a high-voltage cable in the ground (Gasunie, 2022). It is much more efficient to open the whole corridor once, so that TenneT and Gasunie can work together and there will be mutual benefits, for example in terms of costs. Gasunie wants the hydrogen pipeline to be built by 2030, while TenneT wants the high-voltage cable to be operational by 2035. Secondly, the rules for the construction of hydrogen pipelines are still not clearly defined in the national regulations. For safety reasons, hydrogen pipelines are not allowed to be built close to high-voltage cables and natural gas pipelines. At certain smaller points, also known as critical points, there is not enough space to lay all pipelines and cables according to the current regulations. These regulations are set by national governments, but according to the developing industries, there are solutions to bring them closer together.

Void Infrastructure Development (ID):

The regulatory void in hydrogen infrastructure development stems from the absence of clear and coordinated regulations to guide the creation of the hydrogen transportation network. The delay in developing a crucial segment of this network, also known as the Delta Rhine Corridor (DRC), has resulted in a slowed-down implementation. While hydrogen production technologies are ready and waiting for deployment, the lack of certainty surrounding network development is hindering this progress (Gasunie, 2022). This incomplete supply chain requires effective regulatory oversight and decision-making to move forward. The technical implementation of this infrastructure development is slowed down due absence of regulations.

4.5. Case study conclusion

The Hy3$^+$ case offered great insight into the current development and what is hindering the technology and infrastructure development. The positioning of the team as a spider in the web between the various stakeholders offered nuanced insights from which the most important regulatory voids could be identified.
The delays and gaps in the regulatory framework discourage the technology development that is much needed and slow down the development as a result. The failure of the Netherlands to properly address these regulatory gaps poses an extra challenge to the already challenging EU-climate targets.

The absence of a well-structured market and framework significantly stagnates the progress that is desired to be made. The result is that stakeholders are unable to make investment decisions, which slows down the development of the hydrogen supply chain. While some of the technology development is done by, for example, the hydrogen-producing stakeholders, the implementation does not get off the ground. Additionally, there is a lack in terms of coordination in aligning different market parties.
The second identified regulatory void regarding the infrastructure development lacks progress. Since critical parts of the network, like the construction of the DRC, are delayed (Gasunie, 2022); hesitation and proponent decisions are the result. Due to the absence of national safety and operational standards, the development remains ambiguous which further complicates the system integration of the hydrogen infrastructure.
Ultimately, cohesive coordination, cooperation and regulation are needed for both regulatory voids (specifically) to prevent the implementation of hydrogen from slowing down.

This case study and the identified regulatory voids serve as the foundation for the upcoming interviews, as outlined in the interview protocol (Section 3.2.2). The interviews will begin by exploring current barriers without initially introducing them to the interviewee. This approach ensures an unbiased validation, allowing regulatory voids identified in the case study to be independently confirmed without predisposing participants to specific information. Following this initial discussion, the identified voids will be presented and examined in greater detail. Figure 6.1 in Chapter 6 provides a visual representation of these findings, integrating insights from the Hy3$^+$ case study with the primary data collected through the interviews.

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5
Empirical Data Collection and Analysis

This section presents the observations from the Hy3⁺ case study and the interviews conducted with various stakeholder groups. First, Section 5.1 outlines the key observations from the Hy3⁺ case study. Next, Section 5.2 provides an overview of the stakeholder interviews conducted during this research. Finally, Section 5.3 explains how these insights inform the primary data analysis and contribute to answering the second and third sub-questions in Chapter 6: Findings.

5.1. Observations case study Hy3⁺

As outlined in the Methodology Chapter (Chapter 3), two types of observations were conducted: those during the Hy3⁺ sessions (both with and without project partners) and those made at attended hydrogen fairs (not serving as a primary data source). The case study observations provide a thorough and adequate understanding of the evolving hydrogen transition and constitute a key primary data source for this thesis. Developing this understanding is essential for recognising the challenges and effectively addressing regulatory voids. These observations are therefore considered exploratory. The case study findings serve as empirical data, complementing the desk research conducted to identify regulatory voids.

Observations from the case study are predominantly used to identify the status quo and eventually the two regulatory voids: infrastructure development (DRC) and market development. The information is used to gain an understanding of the problems that the implementation is currently facing. Table 5.1 presents the date, the type of meeting and the parties involved in the meetings from the case study.

Table 5.1: Attended Hy3⁺ project meetings with and without partners of the Hy3⁺ case study.

Date:	Meeting name:	Involved parties:
12/06/2024	Biweekly working session	Arcadis and TNO
25/06/2024	Biweekly working session	Arcadis and TNO
09/07/2024	Biweekly working session	Arcadis and TNO
03/09/2024	Biweekly working session	Arcadis and TNO
09/09/2024	Brainstorming session bottlenecks	Arcadis
17/09/2024	Biweekly working session	Arcadis and TNO
18/09/2024	Steerco	All partners (Appendix C)
01/10/2024	Biweekly working session	Arcadis and TNO
15/10/2024	Biweekly working session	Arcadis and TNO

5.2. Interviews with stakeholder groups

An essential component of the primary data collection involves conducting interviews with individuals engaged in hydrogen adoption. These interviews primarily focus on the regulatory voids identified in the Hy3⁺ case study, while also providing broader contextual insights to develop a more in-depth understanding of hydrogen developments from the interviewees' perspectives. This section will therefore discuss the interview analysis strategy, involving the interview protocol, the stakeholder groups that are interviewed and the creation of first order terms and overarching second order themes.

As elaborated on in Section 3.2.1, the goal is to conduct semi-structured interviews that have a certain type of conversation freedom. On the other hand, the structure makes sure that all the subjects are discussed during the interviews. This protocol for the interview can be found in Appendix B. Questions and topics presented in the protocol are obtained from the literature review and the Hy3⁺ case study.

5.2.1. Interview respondents

For interview recruitment, interviewees must have expertise in and experience with both technological development and regulatory processes. In addition, an understanding and affection are required with the status quo and the identified regulatory voids from the case study (Section 4.4). The primary goal of the interviews is to obtain various visions from interviewees about the strategies for overcoming the identified regulatory voids.
The interview respondents are recruited via various methods: the main focus is on the partners who are involved in the Hy3⁺, of which a more detailed overview is presented in Appendix C. In addition to the partners of the case study, a personal network is used and respondents are obtained at the following two fairs: Vakbeurs Energie ('s-Hertogenbosch, October 9th 2024) and the European Hydrogen Week (Brussels, November 19th 2024). In total 20 interviews were conducted, meaning that the minimum number of stakeholders required for each stakeholder group has been reached (see Table 3.2), indicating that information saturation has also been achieved (Wormuth, 2022). An overview of the conducted interviews for the primary data collection can be found in Figure 5.1. The connected interviews are categorised based on each stakeholder group linking to the number presented in Table 5.2.

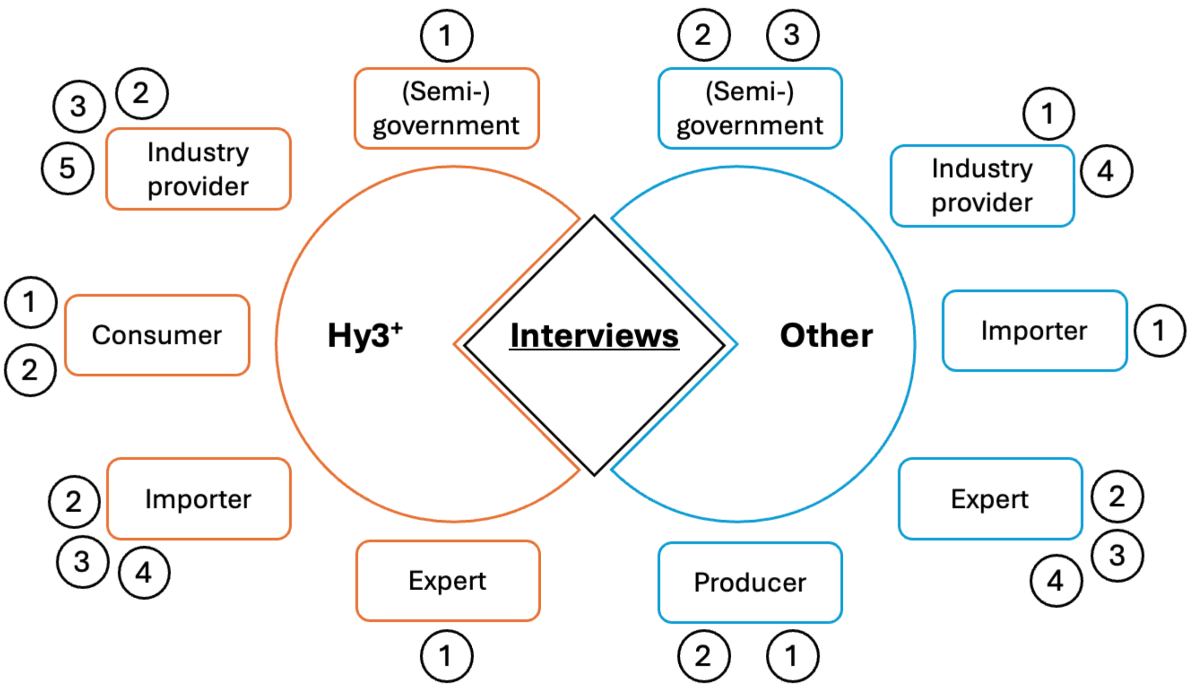

Figure 5.1: Overview of the interviews conducted for the primary data collection.

To give insight into the overviews and the moment of conducting the interviews, Table 5.2 presents a more detailed overview. Additionally, the relation of the interviewee with the Hy3⁺ project is presented in the table. The last column gives a unique code for the interview that will be used throughout this report as a reference. This code will also be used to present quotations from the specific stakeholders, each stakeholder group has a different abbreviation and number, making the transcriptions of the interviews anonymous.

Table 5.2: Overview of conducted interviews including the code for the interview.

#	Stakeholder role:	Case Hy3⁺:	Interview date:	Duration [min]:	Role #:
1	Expert	Yes	11/10/2024	42	Exp 1
2	Hydrogen industry Provider	No	14/10/2024	49	HiP 1
3	Hydrogen industry Provider	Yes	22/10/2024	43	HiP 2
4	Hydrogen Producer	No	30/10/2024	47	HP 1
5	Expert	No	31/10/2024	76	Exp 2
6	(Semi-)Government	Yes	05/11/2024	50	sGov 1
7	Hydrogen Importer	No	05/11/2024	51	HI 1
8	Hydrogen industry Provider	Yes	07/11/2024	56	HiP 3
9	Hydrogen Consumer	Yes	07/11/2024	57	HC 1
10	Hydrogen Consumer	Yes	08/11/2024	86	HC 2
11	Expert	No	11/11/2024	60	Exp 3
12	Hydrogen industry Provider	No	14/11/2024	50	HiP 4
13	Hydrogen Producer	No	14/11/2024	114	HP 2
14	Hydrogen industry Provider	Yes	18/11/2024	59	HiP 5
15	Hydrogen Importer	Yes	21/11/2024	58	HI 2
16	Hydrogen Importer	Yes	22/11/2024	49	HI 3
17	Hydrogen Importer	Yes	25/11/2024	33	HI 4
18	(Semi-)Government	No	06/12/2024	64	sGov 2
19	Expert	No	23/12/2024	32	Exp 4
20	(Semi-)Government	No	15/01/2025	67	sGov 3

5.3. Data analysis overview

The analysis of the interview data, referred to as the primary data input, is conducted following the Gioia methodology. This approach emphasises an initial focus on the raw transcripts of the interviews, ensuring that the analysis remains grounded in the collected data. The objective is to see patterns in the data as a starting point, whereafter the in-depth analysis will be conducted. A brief overview of the analysis process is provided in Figure 5.2. The findings derived from this analysis are presented in Chapter 6: Findings, while their connection to the literature is discussed in Chapter 7: Discussion. The patterns and graphs resulting from the analysis are included in Appendix D.

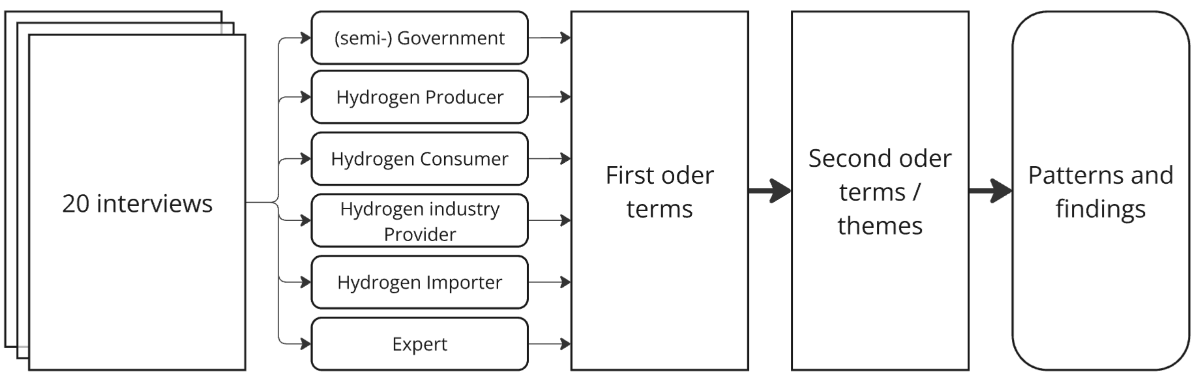

Figure 5.2: Simplistic schematic overview of data analysis.

5.3.1. Research questions and catalogue

In the next step, the text is examined concerning the second and third research questions as presented in Section 1.3.1:

2. *What is the status quo of hydrogen infrastructure and market development?*

3. *How can insights obtained from the current hydrogen development help address regulatory voids in similar future transition scenarios?*

The focus of these two research questions is to further identify the regulatory voids found in the case study and to identify how the various stakeholder groups argue how these voids can be overcome. The codes assigned in the previous step serve as initial findings and are also known as first order terms. To gain a more holistic understanding of the cumulative findings from the interview transcriptions, the first order terms derived from these interviews are collectively categorised into second order themes. This categorisation is also in line with the Gioia method (Gioia, Corley, and Hamilton, 2013). To provide more structure to the interviews for the data analysis, the following second order themes can be found in Table 5.3.

5.3.2. Interview protocol structure

An important role for conducting the interviews and collecting the right data is the interview protocol. For reference, this protocol is earlier discussed in Section 3.2, and is presented in Appendix B: Interview protocol. For the analysis, it is important to differentiate between the different parts of the interview:

1. **Verification and validation:** the first part focuses on checking if the interviewee experiences the current situation related to hydrogen adoption in the same way as the Hy3+ case study and the observations that were made. Besides, open questions are asked to find out what the regulatory voids are according to the interviewee before presenting the regulatory voids. Focussing on the second research question to identify and confirm the status quo.
2. **Strategy exploration:** the second part focuses on the two identified bottlenecks from the Hy3+ case study: hydrogen market development and hydrogen infrastructural development. The goal is to find out what, according to the interviewees is missing in terms of strategies and how processes can be organised to address the regulatory voids.
3. **Future visions:** the final section centres on the future vision of the stakeholder being interviewed. A key time frame is the period between 2030 and 2035; specifically, questions are asked about how the future of hydrogen evolves and what developments will be adopted during that time.

This interview protocol is slightly different for each type of stakeholder that is interviewed. This is done to get a better sense of understanding and to gather critical data from the interviewee. Per stakeholder group the questions are specific to gain a full understanding of the current hydrogen adoption strategies, the complete differentiation that has been made in the protocol protocol is presented in Appendix B

5.3.3. First order terms

This research aims to determine whether institutional theory adequately addresses regulatory voids that emerge during the diffusion stage of the technology development cycle. The Gioia methodology is employed to achieve a comprehensive understanding and facilitate comparisons. This methodology, previously explained in Chapter 3: Methodology, serves as the analytical framework for this analysis. In line with the Gioia method and its usefulness for this research, the analysis is initially conducted from the perspective of the primary data collected. By excluding literature and other potentially interfering theories at this stage, the study ensures greater objectivity, enabling more unbiased comparisons to be drawn.

First order terms concentrate on various aspects discussed by the interviewee, with particular emphasis on the three key areas outlined in the interview protocol: verification, exploring strategies to address the regulatory voids, and envisioning the future. The phrasing of sentences is crucial in gaining insights into elements such as honesty, trust, commitment, and related other factors that describe the progress of hydrogen adoption and implementation. These first order terms can be found in Appendix D, Table D.1 presented in the Appendix outlines the first order terms along with their underlying meanings and interpretations of the terminology. In total, there are 78 different first order terminologies found in the transcripts of the total 20 conducted interviews, Table 5.2 presents the complete overview.

5.3.4. Second order themes

Since the Gioia methodology is the theory used for creating insight into the primary data that is obtained, this is done systematically. Second order themes represent abstract, overarching theoretical constructs developed from the (raw) first order interview data. These themes are essential for moving from specific observations to generalize theoretical contributions and create patterns for higher-level theoretical insights. The focus for the second order terms (also referred to as themes) is on building theory rather than describing phenomena emerging from the data. While the primary objective of the findings is to create insight into the patterns, the ultimate goal is to present the findings in a holistic way that supports the conceptualisation of theory.

Likewise, to the set-up of the research questions and the interview protocol, the construction of the analysis will be in line with these questions and approaches to find the desired outcomes. The goal of the second order themes is to create patterns and provide answers to the main- and sub-questions as described in this research. This is to be found in the second order themes, as they relate to answering and identifying the following structured themes:

- **What** is the regulatory void according to the interviewees? Focussing on answering the second research question that relates to the identification of what the status quo of the hydrogen transition is. Exploring if the stakeholder groups identify the same voids (confirmation) and what the status is.
- **How** do various stakeholders see the regulatory voids being solved? This relates predominantly to the third research question that tries to explore how voids need to be addressed accurately according to the stakeholder groups that are interviewed. Exploring potential well-fitting strategies (that can be related to the Institutional Theory for later analysis) to overcome the regulatory voids.
- **Who** need to and **where** can the regulatory voids be actively addressed? Complementary to how stakeholder groups see the regulatory voids be overcome. However, second order terms related to this category are focussed on deeper identification in solving the void concerning which parties and where in the supply chain/business case.

Table 5.3 presents the nine identified second order terms that formulate the basis for finding patterns based on the sub-questions related to: what, how, who & where. Each second order term is shorty explained, and the last column presents the relation to the structured theme.

Behind this table is a schematic representation, as visualised in Figure 5.3, to identify the patterns in the data concerning the second order terminologies. The linkages between what – how – who & where need to be identified and analysed to find out what parts of the data have a pivotal role. As in line with the research questions, the interview protocol and the case study; it is first important to identify what the status of the hydrogen implementation is, before being able to answer the how and who & where questions related to the development and addressing the regulatory voids accurately.

What – how links:

The relationship between what and how provides insight into the underlying structures (what) that enable or constrain actionable (hydrogen) strategies (how). Identification of these links is critical for analysing the mechanisms that drive change in addressing regulatory voids. To ensure robustness, it is essential that these findings are validated through stakeholder feedback (interviews) and compared with existing literature to confirm alignment or identify gaps in theoretical understanding (discussion). The what-how links emphasise that foundational elements such as regulatory frameworks, capacity-building initiatives and infrastructure development are (pre)conditions for enabling adequate strategies. These findings need to be validated through stakeholder interviews and compared with existing literature on how to address the regulatory voids. This comparison will determine whether the proposed linkages are consistent with theoretical findings or reveal new patterns.

Table 5.3: An overview with the explanation of the second order terms.

2nd order term:	Abbr.:	Explanation:	What/how/ Who&Where:
Regulatory Guidance and Standardisation	RG&S	Relates to the regulations and standards that are in place related to the industry development.	What, How
Trust and Transparency Creation	T&TC	Concerning the trust development and the transparency between different industry parties and government bodies.	How
Cooperation and Stakeholder Integration	C&SI	Interaction and cooperation between the various stakeholders that are concerned with the hydrogen development. Also, the integration of the stakeholders within the system is regarded.	What, How
Economic Incentives and Market Stimulation	EI&MS	Stimulation and economic incentives that are developed and implemented in the system or should be implemented.	How, Who & Where
Knowledge Development and Capacity Building	KD&CB	Relates to the development of new techniques and the capacity that is needed for the developing technology to gain momentum.	What, Who & Where
Infrastructure and Technology Development	I&TD	Concerning the technical and infrastructural (when needed) aspects of the hydrogen technology adoption and development.	What
Long-term Vision and Strategic Goals	LV&SG	Strategic goals and long-term visions are set by government bodies, industry parties themselves, society and other individuals.	How, Who & Where
Market and Institutional Adaptation	M&IA	Concerning the development market structure and the institutional and organisational set-up/adoption that needs to be in place.	What
External Pressures and Policy Drivers	EP&PD	Pressure from among others society, governments or industry parties that have the desire to make the technology adoption happen.	How, Who & Where

How – who & where links:
The how – who & where linkages address the operational and practical considerations of policy implementation, as a step further than the previous link identification. Identifying which actors are critical and where efforts should be focused, enabling targeted action to address regulatory voids. Validation of these findings through stakeholder input and comparison with case studies and the literature might ensure useful patterns. Since this is a second step and not the primary scope of this research, not always concrete links are identified. The main goal of this research is to determine what are the regulatory voids and how strategies can effectively address these voids.
The 'how – who & where' links emphasise the importance of identifying key actors and locations for targeted action. Validation through stakeholder feedback ensures that these links reflect practical realities, while comparison with existing literature provides a theoretical underpinning. Having this dual approach ensures that the findings are both actionable (practically) and theoretically (academically) reflected.

5.3.5. Normalisation of data

In addition, to ensure clearer data representation and to prevent findings from being overlooked, the data has been normalised to provide a holistic view. This approach enables data from different sources or scenarios to be directly compared, which is particularly valuable in multidisciplinary research. There are various methods to normalise such findings, for instance, based on the time spent per interview or the number of interviews conducted per stakeholder group.
In this research, multiple stakeholder groups were interviewed. Some groups, such as the Hydrogen Industry Provider (interviewed five times), are more represented than others (for example

(semi)-Government two times). To create a more balanced representation across the different stakeholder groups, the responses have been normalised based on the most represented group: the Hydrogen industry Provider (HiP). This group provided a total of 273 responses, which served as the benchmark for normalisation.

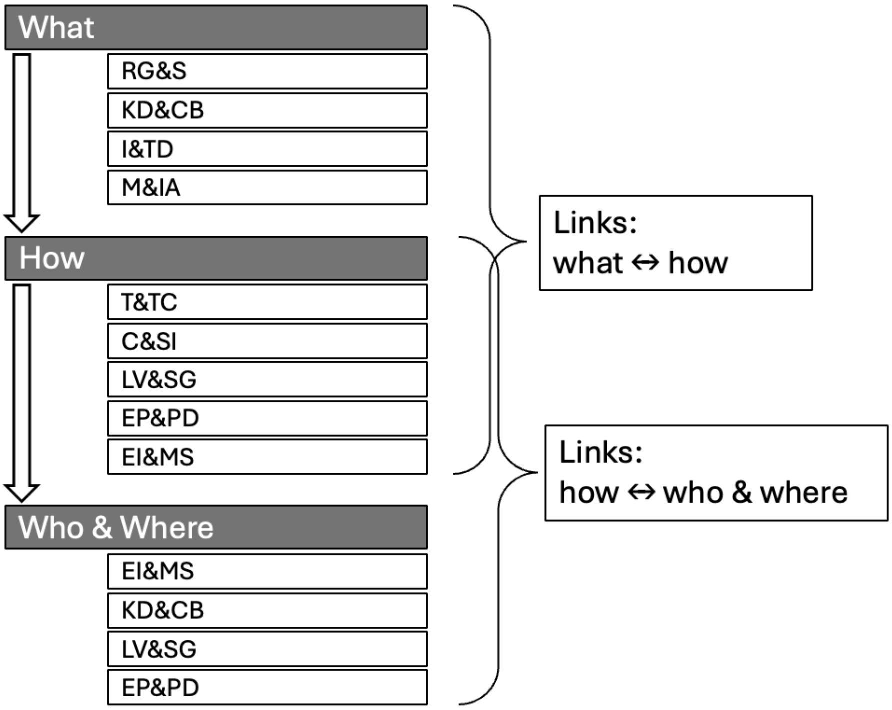

Figure 5.3: Analysis and findings visualisation framework (made by author).

5.3.6. Presentation of data

The processed interview data is presented in the next chapter, Chapter 6: Findings, and includes quotes from various stakeholder groups to improve understanding. Additionally, the data obtained from these interviews is provided in Appendix D: Findings, this is the cumulative data representation and graphs are made based on the answers from the interviews and how the responses link to the second order themes. Section D.1 presents the figure that is objectively derived from the data, normal visualisation. Section D.2 presents the normalised data based on the most responses from the Hydrogen industry Provider (HiP) to create equality in the data representation based on the maximum number of responses. The last section of the appendix, Section D.3, presents the responses from the interviewees related to the two identified regulatory voids and the relation between the second order themes. This Appendix D includes also Table D.2, summarising all fundamental quotes that are used. Furthermore, these quotes from this table are compiled in a supplementary A3-format attachment, offering a complete overview that can be used while reading the next two chapters and allow for better understanding.

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6 Findings

The goal of the findings is to provide answers to the second and third sub-questions of this research, supporting the main question to be answered:

2. *What is the status quo of the hydrogen technology development?*

3. *What are effective strategies on how regulatory voids can be overcome?*

The first section will provide an answer to the second sub-question, confirming the regulatory voids from the case study and presenting the status quo of the hydrogen transition. The current status of the hydrogen transition is already explored in Chapter 4, where the two regulatory voids were identified and defined. To get a full understanding of the developments within the hydrogen transition, the first part of the interviews was dedicated to confirming the voids and creating a complete understanding of the status quo and the regulatory voids regarding the hydrogen transition. When the second research question is answered, the findings will provide an answer to the third research question before moving to the discussion.

To allow for better understanding while reading this chapter, it is recommended to keep the attachment[1] 'Summary overview of interview instances' on the side. This attachment presents all the important quotes from the interviews and will provide a greater understanding of the hydrogen transition.

6.1. Status quo of the hydrogen transition

To obtain a holistic understanding of the regulatory voids and the challenges that were introduced from the case study, the first part of the interviews is dedicated to creating verification. Figure 6.1 was created based on the information obtained from the interview transcripts. Within the figure, the points of stagnation are currently withholding the hydrogen transition from making progress. The points of stagnation are the same points that were identified in the case study, the two regulatory voids: market development (MD) (Section: 4.4.1) and infrastructure development (ID) (Section: 4.4.2). Figure 6.1 is based on the three prominent segments of the supply chain: production, transportation, and consumption. The colour of the boxes represents each stakeholder group identified, likewise as identified in Table 3.2. In addition to identifying regulatory voids, the current potential development processes are represented by dotted lines, illustrating the ongoing alternatives under development within the hydrogen transition to stimulate progress, as indicated in the interview transcripts.

The interviewed stakeholders emphasise two regulatory voids that are presented in the figure in the diamond-shaped boxes. These regulatory voids are primarily situated in the figure towards two stakeholders that are foremost related to these regulatory voids. The Infrastructure Regulatory void is mostly dependent on progress from the (semi-)Government and the Market Development void is situated at the Hydrogen Consumer stakeholder. Although these voids are presented in Figure 6.1 in the colour of these two stakeholders, it does not mean that only these stakeholders can address the voids. This becomes, among other things, visible in the figure regarding the connections (presenting the dependency) that these voids have with developments and responsibilities from other stakeholders.

[1]Both Table D.2 and the separate attachment (which (in small) can be found in Section D.5) present an overview of all the important quotes from the interviews per identified stakeholder group and second order theme.

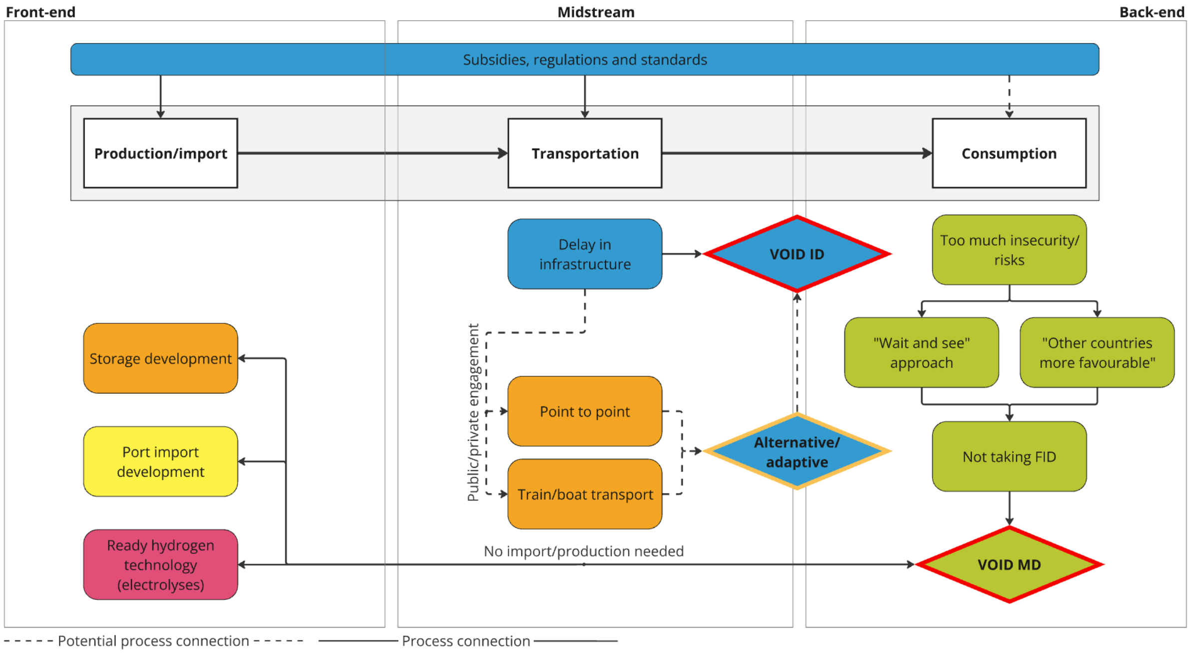

Figure 6.1: Status quo of the hydrogen supply chain development with regulatory voids (blue = (semi-)Government, green = consumer, orange = industry provider, pink = producer, and yellow = importer) (made by author).

Likewise, the alternative adaptive option that came forward during the interviews is situated at the Hydrogen industry Providers but has affection with other stakeholders as well.

Before answering the second sub-question, the interplay of the two regulatory voids is first more extensively discussed in the next two sub-sections.

6.1.1. Void: Market Development

The transcripts of the interview highlight the importance of the market to be developed. Foremost the Hydrogen Producers highlight the fact that technical development like electrolysers is developed and tested, but waiting for implementation. Thereby, Hydrogen Importers additionally are preparing terrains at import ports to create the opportunity for hydrogen to be imported at various locations. In addition, the Hydrogen industry Providers are developing storage opportunities in these ports to make (temporary) storage available at the desired locations. Connecting demand and supply is essential for development and creating a buffer (creating redundancy) will help overcome occasions where supply and demand are not met. From various governmental levels, these incentives must lead to the European hydrogen production and import goals (European Commission, 2022b). The following quote describes the lack of progress that is made and the result of the stagnation [HiP 5]:

> *"Ultimately, it is the end-user who funds the entire supply chain. If they remain uncertain, it becomes difficult for the rest of the chain to make concrete investment decisions. While progress can be made in terms of engineering and planning, significant investments will only be made if there are sufficient binding contracts in place that allow development and guaranteeing the use of the infrastructure." [#44]*

To allow progress, the end-users (the Hydrogen Consuming industries) must facilitate the use of hydrogen before the technological hydrogen developments can be implemented. According to the Hydrogen Consumers, the risks are too big to make investment decisions and allow the industry to align with the hydrogen transition. Therefore, Hydrogen Consumers are taking a 'wait-and-see' approach, delaying the change in the industries. To take away risks, support in terms of subsidies can be obtained from Dutch and/or European subsidy schemes that are in place. The following quote will illustrate the aforementioned and the attitude of the Hydrogen Consumers [HC 2]:

> *"The risks are too great for us to make FIDs, and the lack of clarity in regulations makes it complex for us. We are willing, but not yet able." [#43]*

The current status of the hydrogen transition is lacking the ability to implement the developed technologies, disallowing the possibility to scale up and form a market. In this case, due to the Hydrogen Consumers have difficulties moving forward by not taking FIDs resulting taking a wait-and-see approach. In addition, the potential market that there could be in the Netherlands is not as favourable as other countries. The prices of green energy are high, the subsidies are less sufficient, and in the Netherlands and Europe, regulations are experienced as stricter. As a result of this, industries argue to move to more financially favourable conditions or the need for a level-playing field, [HC 1]:

> *"A level playing field within the EU would significantly contribute to the stability and predictability of investments, reducing the incentive for industries to relocate to more favourable regions of the world." [#23]*

This quote shows the need for guiding regulations and subsidy schemes to support stakeholder groups, like the Hydrogen Consumer, to take an active part in the hydrogen transition. While these frameworks and schemes are already constructed on various levels (SDE++ (Ministerie van Klimaat en Groene Groei, 2024), REPowerEU (European Commission, 2022c), et cetera), there is a need to stimulate end-users or create other incentives to allow construction of the market and create up-scaling. The strategies already developed, as well as potential incentives to address the regulatory void in market development, are discussed in Section 6.2 of this chapter.

6.1.2. Void: Infrastructure Development

The second regulatory void: Infrastructure Development, that was identified in the case study, was also acknowledged within the interview transcripts. Due to the absence of announced infrastructure plans, stakeholders emphasise the difficulty of making progress within the hydrogen transition. Technologies that are developed, are unable to be broadly implemented due to the absence of hydrogen infrastructure. Without the construction of infrastructure, especially the DRC, the production of important is not able to connect to up-take locations. The only announced area that will start using green hydrogen by 2030, is the Rhine-Ruhr area (located in Germany), the need for infrastructure towards that area is illustrated with the following quote [HiP 3]:

> *"The DRC serves as a lifeline, enabling transit to the hinterland (Rhine-Ruhr area) and connecting the various industrial clusters within the Netherlands. The importance of the DRC for national and cross-border connectivity cannot be overstated." [#5]*

The absence of infrastructure and the delay in the announced plans that were presented, the development of hydrogen will ultimately be slowed. Leading to among others the incompletion of the market and thus also the development and upscaling of technologies. At this critical point where industries need to make decisions in line with hydrogen development, delays in plans like these result in a restrained attitude. Further undermining trust in development plans and the creation of the hydrogen market as becomes clear from this quote [HI 2]:

> *"Stakeholders had anticipated the DRC to be operational within a specific time frame. However, the absence of guarantees regarding its operational date introduces new challenges and undermines trust." [#11]*

According to interview transcripts, the absence of trust leads to increased hesitation among the stakeholders, and announcements like infrastructure delays will also delay investment decisions, creating more hesitation for the development of the hydrogen market. Stakeholders highlight that trust

is needed for navigating uncertainties and overcoming unexpected situations like the DRC delay.
New challenges from this quote refer to the need for additional challenges that there will be concerning the development of the DRC. These challenges highlight that an adaptive approach can result in (temporary) alternative solutions. Stakeholders express that inland shipping or train transport alternatives can be of value to them. Transport by a point-to-point connection will allow stakeholders to create a market opportunity in this stage of the hydrogen transition. However, stakeholders argue that current standards and regulations need to be changed to support these developments: safety standards and the correction factor (Nationaal Waterstof Programma, 2024b).

6.1.3. Summary status quo hydrogen transition

So, as becomes clear from the transcripts of the interviews, the underlying causes that cause stagnation in the hydrogen progress are the voids of market development and infrastructure development. The interviews provided an additional holistic understanding of these voids and added to the information derived from the $Hy3^{+}$ case study. The market cannot scale up, not allowing developed technologies to be implemented and add to the hydrogen transition. End-users take a wait-and-see attitude or argue to move to more favourable places (level playing field issue). Highlighting the need for more guiding and supporting government strategies to be applied; foremost dedicated to the end of the supply chain. In addition, the infrastructure delay results in a lack of trust, the creation of hesitation and the need for adaptive approaches. The next sections will show results regarding the strategies to address these voids more specifically.

6.2. Strategies to address regulatory voids

Strategies to address the two regulatory voids that are discussed in the interview transcripts are presented in this section.

6.2.1. Trust and transparency creation

The analysis of the interview transcriptions shows that there is a lack of trust from industry parties towards governmental goals and decision-making. The responses mapped to the second order term Trust & Transparency were relatively low while on the other hand many responses can be mapped to Collaboration & Stakeholder Integration. In order to create a collaborative environment, trust within an unclear environment is essential to create the integration and commitment (Walker et al., 2010). To further elaborate on trust in the hydrogen transition, misleading promises from the past and current announced delays in the development of the DRC, stakeholders seem to lose this trust. Quotations of various interviewed stakeholders are in line with what [HC 1] makes clear in the following quote:

> *"The cancellation of the DRC has weakened trust across the entire supply chain. For Rotterdam, this figuratively places us in an 'island mode,' which is problematic as it removes a critical link in the network." [#51]*

The cancellation of announced plans like these affects the overall trust and confidence among stakeholders, it signals unpredictability in planning and decision-making, resulting in the absence of participation from stakeholders towards long-term goals and a collaborative environment. Further trust is weakened, as the quote incentivises, due to the absence of clusters being connected, which creates greater risks that must be taken. More risks and less trust, make stakeholders hesitant about making investment decisions that are needed to move forward in the hydrogen transition. The relation between trust and making investment decisions is further elaborated on in the discussion (Section: 7.1.1). Many first order responses can be categorised in the second order terms of Collaboration & stakeholder Integration, which contradicts the relatively low responses that can be categorised under the Trust & Transparency creation. Interestingly, stakeholders highlight the need for collaboration to move forward in this 'slow' hydrogen transition, but are complaining about general trust and transparency within governmental plans [Exp 3][HiP 5]:

> *"The transition is progressing very slowly, and there are several reasons for this. One key challenge is the inconsistency of government policies. With each new development, existing plans are often discarded, which hinders progress." [#52]*

Commitment and trust towards announced plans drop and thus limit industries in taking the collaborative and active role to make progress. Thereby industries note [HI 2][HiP 3][sGOV 3] that other parts of the world develop faster due to greater security provided by governments, here trust is (historically) obtained between public and private stakeholders. As elaborated by the interviewed stakeholders, promises from the past are kept, and hydrogen transition plans are (still) stable; therefore, the hydrogen industries have trust in China's future hydrogen market.
Generalised trust, which reflects societal confidence in the reliability and goodwill of institutions and other stakeholders, plays a crucial role here. It fosters cooperation and enables industries to invest and innovate without fear of unexpected regulatory shifts or unmet governmental commitments. The way of gaining this sort of trust is thus crucial for the hydrogen transition progress; industries like Hydrogen Consumers may maybe more committed to the process and take more risks. The connection between taking risks and having trust in other parties will be discussed in Section 7.1.1.

6.2.2. Resource allocation to allow sale up

Hydrogen is not a new type of fuel; its production technologies have been developed over the past, and various industries already make use of hydrogen today (WHA International, 2020). Regulatory voids emerge from the inability to apply developed technologies effectively, preventing their scale-up predominantly due to the absence of clear supporting frameworks. This issue is illustrated in the following quote, referenced by multiple stakeholders [sGOV 2][HI 1][HI 3][HiP 3]:

> *"The current approach suffers from siloed thinking and an excessive focus on market mechanisms, with limited proactivity from key players who prioritise investor returns over societal impact. The lack of vision and leadership from the national government, combined with uncertainties around investment horizons and risks, reinforces a wait-and-see attitude. Decisive action and a clear, guiding vision are urgently needed to address these challenges." [#40]*

The reference to 'siloed thinking' and an 'excessive focus on market mechanisms' highlights the need for improved resource allocation. Market mechanisms in this context refer to regulations and subsidies, such as RED III (Rijksdienst voor Ondernemend Nederland, 2025), SDE++ (Ministerie van Klimaat en Groene Groei, 2024), and the Hydrogen Bank (European Commission, 2023). Stakeholders emphasise in the transcripts that the fragmented approach to resource distribution prioritises the front end of the supply chain, like the development of electrolysers, while neglecting support for the back end of the supply chain.
The current state of the hydrogen transition highlights the importance of investment decisions by Hydrogen Consuming (HC) parties. As the quote and analysis of stakeholder interviews reveal, this stakeholder group is adopting a 'wait-and-see' attitude due to unforeseeable risks and a lack of governmental support to mitigate these risks. This situation underscores the pressing need for clear, long-term visions and policies that balance market dynamics with targeted subsidies to bridge the investment gap. In Section 7.2.1 of the discussion, the type of need will be discussed.

Stakeholders [HI 1][HI 3][HiP 3] further elaborate on an underlying issue, stressing that stimulating developments across the entire supply chain (including transportation) provides opportunities for the implementation of developed technologies, such as electrolysers. By focusing on incentivising the back end of the supply chain to stimulate hydrogen adoption, demand for production would naturally increase. Enabling production to scale up, facilitating the implementation of existing technologies and creating opportunities for the development of future innovations (Kenton, 2024). The economies of scale principle becomes applicable, including cost reductions and improved efficiencies.
Additionally, stakeholders underscore the importance of sector coupling to further incentivise hydrogen adoption and support the broader development needs of the supply chain (Van Nuffel, 2018). This

integrated approach would enhance the scalability of hydrogen technologies while aligning production, transportation, and consumption to create an integrated transition pathway.

6.2.3. Mission driven regulatory development

A reoccurring issue regarding regulatory development is it is often directed to resolve specific issues that arise, like focusing on the stimulation of electrolysers. Resulting in scattered and fragmented regulations affecting parts of the hydrogen supply chain; lacking a mission-driven approach. This scattered and fragmented development lacks clear long-term goal development and the creation of a joint vision is elaborated with the following quote [HC 1]:

> *"It's a complete circus of small taxes, innovation subsidies, and countless schemes. Pulling and pushing in all directions, with no single authority or individual overseeing everything simultaneously. The European Commission, national governments, and companies are constantly in dialogue, asking, 'Is this enough? Will it happen?'." [#30]*

Hydrogen Importers and (smaller) Governments agree with this quote, thereby they experience the lack of central steering from a government body. As the quote and they emphasise, governments are insecurely asking questions about whether it is enough and how regulations should be structured, showing a lack of concrete decisions and actions. Industry parties like steel and refineries need guidance instead of responding to market failures. In addition, hydrogen import ports are uncertain when future imports will start and how this hydrogen must be transported to the industries. Central steering is emphasised by various levels of governments that have plans that are in line with each other, from European to national level.
Thereby, the Hydrogen Consuming industries argue the need for a level playing field to create sound investment decisions. They argue that there are pricing differences on a world scale. Hydrogen Producers argue that there are even price differences between the Netherlands and Germany, differences in green electricity prices and grid connection fees. As Hydrogen industry Providers emphasise the risks of industries that might move to more favourable locations, potentially outside Europe, [HiP 3]:

> *"It is concerning to see that some parties are considering relocating, and in some cases, it's already happening, both in Germany and the Netherlands. This is unfortunate because moving industries elsewhere does not solve the problem of the energy transition. It simply shifts it to another location, potentially making it even more polluting." [#29]*

Multiple interviewed stakeholders like Experts, Governments and Hydrogen Consumers state quotations that are in line with the presented one. For the European market and labour development, it is crucial that industries remain located here (Van Bree, 2023). In addition, the quote illustrates that potential sustainability goals are in danger, and less strict pollution regulations might be relevant in other locations.

Both quotes underscore the need for a 'mission-driven' approach: aligning efforts, resources, and policies across stakeholders (both public and private) to create overarching long-term goals developing a collaborative environment to address the large-scale challenges. Governmental interviewee [sGOV 1] announced during the interview that currently there are public-private partnerships being developed. Both Hydrogen Producer [HP 1] and Hydrogen Importer [HI 4] acknowledge that there are tailored agreements (maatwerkafspraken) being developed. According to them, these agreements focus on consuming industries (the back end of the supply chain) that have the lowest investment gaps and thus have the most potential to take up hydrogen in their processes.

6.2.4. Guidance from various levels of government

Besides a mission-driven approach, there is a lack of guidance related to regulatory development. The transcripts of the interviews reveal that special attention must be paid to the development of standards, predominantly related to infrastructure developments. An important aspect that must be developed is the development of infrastructure: the backbone that must distribute hydrogen from product and import to the consuming industries in the hinterland. While announced infrastructure plans, like the development of the DRC, are delayed and undermining the trust; there is an additional need for clearance and transnational cooperation emphasised by Hydrogen Consumers [HC 1] and Hydrogen industry Providers [HiP 1]. Current hydrogen-related infrastructure plans are based on the Dutch national gas law, causing difficulties regarding the context of these standards [HC 2]:

> *"The gas package, spanning roughly 160 pages, outlines regulations for every aspect of gas transport. These rules, originally designed for an established gas network, are now being applied directly to hydrogen, despite the fundamentally different context." [#20]*

While the national government argues that this provides a solid base and a starting point, also is acknowledged that certain aspects remain undefined [sGOV 1]. Resulting in a complex puzzle that needs to be solved. Various stakeholders emphasise the need for a network [HiP 5][HC 2][HI 3] to create a solid supply chain network. An Expert [Exp 2] highlights, that when Rotterdam is not connected to the Rhine-Ruhr area (Germany) fast, Rotterdam has limited value and remains in an 'island mode'. Without connection, it cannot distribute hydrogen and only facilitate locally connected industries in Rotterdam (an island).
Difficulties arise when cross-border connections need to be made from for example the Netherlands and Germany. These difficulties exist in the differences in standards that are differently defined in both countries. Hydrogen Importer [HI 4] therefore states the need to develop transnational EU standards to overcome differences, ensuring compatibility in infrastructure developments to facilitate hydrogen transport. Developing regulations at the national level is considered easier and faster, before European standards are developed it will take years of developments and mitigations between countries to create unity, this is discussed in Section 7.3.1 of the discussion.

6.2.5. Adaptive process development

As governments and stakeholders make clear in the transcriptions of the interviews, there are certain regulations and subsidies in place (e.g.: RED III (Rijksdienst voor Ondernemend Nederland, 2025), SDE++ (Ministerie van Klimaat en Groene Groei, 2024), and the Hydrogen Bank (European Commission, 2023)). The need for market creation is emphasised in a way, but still, a real market remains underdeveloped. Thereby, the delay in infrastructure developments is not helping the market to progress; simply supply and demand are not connected. Alternative routes for the development of hydrogen transport can be found by inland shipping or by train [HI 3][HC 1][Exp 2]. While standards are not fully developed in the Netherlands regarding the transport of hydrogen via this method, stronger cooperation is needed to accommodate progress. A Hydrogen Importer elaborates that public-private partnerships are needed between the industry players and the government to achieve progress [HI 1]:

> *"Establishing this public-private partnership is essential, as neither the government nor the private sector can achieve this alone." [#3]*

To overcome obstacles like the DRC delay, the need for an adaptive process is needed. Stakeholders emphasise that they need to temporarily overcome situations like these to make a chance to start market building, an option that Hydrogen industry Providers [HiP 3, HiP 5], Hydrogen Consumers [HC 1, HC 2] and Hydrogen Producer [HP 2] explain is the creation of point-to-point connections. They argue when they want to realise this, they need cooperation from the government as well. While the refinery route (train route from NL to DE) has been exposed to a correction factor of 0.4 [HI 3], adaptive problem-solving is a constraint. Therefore, incentivised is to start cooperating and create creative solutions to be able to navigate problems [Exp 1][HiP 3].

6.2.6. Governmental organisation and structure

A last interesting finding that is important to elaborate on, is regarding the structure of certain (semi-)governmental organisations. Both Hydrogen Consumer [HC 2] and Hydrogen Importer [HI 1] address the principal-agent problem that is created between KGG (former EZK) and Gasunie (semi-government responsible for gas network development. The following quote elaborates on the principal-agent problem as it is experienced by the Hydrogen Consumer [HC 2]:

> *“The structure of the government hinders progress in the hydrogen transition. KGG (former EZK) aims to promote the hydrogen economy, boost employment, and deliver societal value, while also ensuring a good return on investment. However, Gasunie holds a monopoly over the hydrogen infrastructure, with its own financial priorities. This misalignment of goals creates a principal-agent problem, where societal and industry ambitions risk being overshadowed by the agent’s self-interest.” [#14]*

While KGG wants to achieve societal and industry goals, they are not fully aware of the progress that Gasunie is making. Gasunie has more expertise in the field of hydrogen infrastructure development, creating information asymmetry. As the Hydrogen Consumer suggests [HC 2], Gasunie might have its own goals like maximising financial returns. While Gasunie holds a monopoly position for the creation of the hydrogen network, they can develop at the preferred speed that is most favourable to them. When there are no incentives for them to develop infrastructure or more players that can develop, the developments can be drastically slowed down; ultimately resulting in the existence of the principal agent problem. The hydrogen importer [HI 1] argues that this is the case regarding the DRC delay. Addressing the principal-agent problem between governmental institutions, like Gasunie and KGG) in situations like the hydrogen transition; will be discussed in Section 7.3.2.

7
Discussion

Now that the findings have been outlined in Chapter 6: Findings, this chapter aims to relate the identified instances to theoretical frameworks. The findings from the interviews are linked to the theories discussed in Chapter 2: Literature Study, allowing the researcher to make interpretations.

This chapter maintains a strong connection to the instances found in the interview transcripts. A summary of the most significant insights from the interviews is presented in Table D.2. However, it is essential to ensure comprehension while reading the discussion. To support this, an attachment is provided at the end of this research (or as a separate file) which helps create understanding while reading the discussion simultaneously[1]. References within the discussion will be indicated using an index number in the format *[#XX]*, corresponding to the relevant instance in the separate attachment. The quotes referred to will enlarge the understanding of the surrounding text.

Section 7.1 examines the essential conditions for enabling successful transitions, focusing on trust-building, regulatory design, and resource allocation. Thereafter, the development of the hydrogen market is linked to theoretical concepts such as economies of scale and sector coupling. The third section discusses government structures, including incentives to mitigate principal-agent problems; predominantly regarding the infrastructure development void. Finally, the chapter concludes by outlining the limitations of this research and providing suggestions for future studies.
This discussion follows the abductive character of the research; iteratively refining the understanding of regulatory voids in hydrogen infrastructure by integrating insights from the literature, $Hy3^{+}$ case, and interviews. This approach allows for the identification of emerging patterns and conceptual advancements, ensuring that the discussion remains connected to the empirical data collection and reflects theoretical insights obtained.

7.1. Foundational aspects for successful transition development

This part of the discussion focuses foremost on the development of trust, goals, vision, guidance and lastly the creation of a mission-driven mentality among the stakeholders involved.

7.1.1. Trust as a basis requirement

From the stakeholders' perspective [#52][#53] becomes clear that there is a lack of trust in making investment decisions and the general progress of the hydrogen transition. The delay in infrastructure plans [#51] and the loss of trust due to decisions in the past [#50], have a negative effect on the transition. When analysing the interview responses based on a categorisation of second order themes, there exists a relatively low number of responses that are related to this theme. While in contradiction there is a huge number of responses that are related to the second order theme of collaboration and stakeholder integration.

To better understand the essence of 'trust,' it is important to clarify the specific type of trust referred to by the interviewed stakeholders. This development of trust relates foremost to the relation between hydrogen-developing industries (that need to make investment decisions in line with the hydrogen transition) and governments (that determine the process and long-term goals of the hydrogen transition

[1] For online use, it is recommended to view the attachment on a separate screen. For printed use, it is advisable to place the attachment alongside the physical report.

by setting the conditions). The type of trust that is relevant between governments and developing industries, can be categorised as ‘institutional trust’ (Fuglsang and Jagd, 2013). This type of trust refers to the belief that institutions (government bodies) will act competently, predictably and in alignment with established rules, values and long-term goals/visions. When institutions are strongly developed in line with the institutional theory processes: regulative, normative and cultural-cognitive; these institutions can enable and inspire at an inter-organisation level via trust relations. To build trust relations, both institutions and industry stakeholders must engage in collective sense-making processes to bridge the gap, involving (Floyd et al., 2011):

- **Overcoming ambiguities:** governments need to communicate clear, actionable goals. Industries must make their expectations and limitations (development constraints) clear.
- **Creation of shared understanding:** stakeholders must develop a mutual understanding of risks, insecurities, challenges, and opportunities.
- **Adaptive environment development:** technologies and policies are evolving in transitions, requiring both actors and governments to remain adaptive.

In order to address the market development void, stakeholders must overcome their wait-and-see attitude [#35]. In addition, governments must develop clear regulations and long-term goals that are realistic and up to the expectations of the actors [#21] (setting the conditions). In this way, trust between the public and private sides can be built, having a positive effect also on future transitions and allowing for progress instead of a passive attitude (Heitler, 2012).

7.1.2. Creating clear goals and visions

The development of clear goals and long-term visions is part of the development of trust and transparency between public and private parties. However, instead of just addressing it, there is a need to discuss how these goals and visions can be established.
The findings show that, among others, hydrogen consumers [#20], industry providers [#21] and Experts [#6] reveal the need for regulatory clarity and guidance provided by the two levels of government: national and European. The institutional theory emphasises the need for goals that pressure developments of the hydrogen transition (Scott, 1995). On the one hand, the theory elaborates the need for selection pressures, such as the CO2-price (Emissieautoriteit, 2022) that in a way forces industries to move towards a cleaner and more sustainable system. On the other hand, there are more adaptive mechanisms that include setting goals and subsidies to stimulate development. These adaptive mechanisms can be found in the form of the Hydrogen Bank (European Commission, 2023), SDE++ (Ministerie van Klimaat en Groene Groei, 2024), and REPowerEU (European Commission, 2022c) for example.

As becomes relevant from the analysis of the stakeholders’ interviews, the need for a more clear and structured vision is needed. According to stakeholders the current goals and regulations in place are chaotic and unstructured [#30], and industries do not know what is applicable to them. Additionally, goals are often not reached, they are too optimistic leaving them ultimately worthless [#16]. The hydrogen transition in general is an open-ended transition (Dall-Orsoletta, Romero, and Ferreira, 2022), where no parties know exactly how the transition will evolve [#22]. The national government and the EU need to set the standard for development and the pace, this can be done in a progressive way to stimulate development and show potential. REPowerEU sets therefore the future hydrogen goal of the production and import of 10 million tonnes of hydrogen by 2030. According to forecasting studies, this goal will not be met due to a too big implementation gap that needs to be covered (European Commission, 2022c).
Establishing new collective goals, which account for market expectations across various segments (such as the front-end and back-end of the supply chain), will help define clear objectives and enhance motivation towards achieving them. This approach ensures that efforts are directed toward collective goals (both private and public), rather than pursuing objectives that are unlikely to be realised.

7.1.3. Legitimacy: resonating to norms

Goals are hard to translate from a European level into the national level and vice versa [#53] (Pope, 2020), resulting in a loss of legitimacy (Jeong and Kim, 2019) and regulatory clearance. Legitimacy refers to something being inherently right, aligning with the natural order or how things should be.

(Zelditch, 2020). The principle of legitimacy is strongly embedded in the normative process regarding the institutional theory (Scott, 1995). by focusing on how institutions align with societal values and norms to maintain this legitimacy principle. Institutions embed legitimacy into their practices through the creation of formal rules, procedures, goals and norms. In the case of the hydrogen transition, the regulations and goals that are created regarding the development are needed to resonate with the beliefs of the industry actors. What can be seen from the findings, is that these norms do not always seem to resonate with the current status of the development, slowing down the process and not reaching hydrogen transition goals as they were set. An underlying problem is that these norms and goals are too abstract according to them and therefore not applicable. For example, the REPowerEU goals are too abstract and the in-place regulations are fragmented because they are not (yet) translated from the European level to the national applicable levels.
To make goals more tangible and legitimate, countries could make national hydrogen goals to incentivise hydrogen adoption. Thereby shorter goals, year-to-year for example, can have a positive result due to industry actors being more frequently confronted with the current status of transition progress (Harackiewicz, 2000). Involving the industry players within these development goals and norms will help to create understanding from both sides of the spectrum. Emphasising the base of the normative processes: when norms are not socially accepted, they will be neglected, and chaos will arise. Although actors understand that this for national and European intuitions is a hard puzzle to solve, they need to set certain conditions (standards and regulations) that resonate with the current development.

To make hydrogen transition goals more tangible and legitimate, it is recommended that countries create clear national hydrogen targets to incentivise adoption and progress. These national hydrogen targets need to be based on the European target to align countries but also create a certain type of independence (Bürgin, 2014). Additionally, setting shorter-term (phased goals) can positively impact the process by providing regular updates on progress and ensuring that industry actors remain engaged with the current status of the hydrogen transition (Harackiewicz, 2000). Furthermore, actively involving industry players in the development phase of these goals and norms is crucial for the creation of mutual understanding and alignment between stakeholders, both public-private and between national and international.
This approach aligns with the origin of normative processes from the institutional theory, which emphasises that norms must be socially accepted to be effective (Scott, 1995). When norms lack acceptance, they risk being disregarded, ultimately leading to inefficiencies and delays. While actors acknowledge that creating coherent standards is a complex challenge for national and European institutions [#22], these institutions need to set norms that resonate with the current stage of development, this will not only improve legitimacy but also facilitate a smoother transition towards the integration of hydrogen into the system.

7.1.4. Mission-driven mindset

The absence of trust, unclear regulations, and stakeholders struggling to align with existing norms lead to fragmentation. Advancing the hydrogen transition requires fostering a collective mindset among stakeholders, driven by a shared mission to achieve sustainability goals and overcome obstacles: a mission-driven approach (Y. Wang, 2011). Findings indicate that stakeholders, such as Hydrogen Importers [#3], stress the need for public-private partnerships, as neither the private nor the public sector can drive progress alone. Both governments and industry actors highlight the importance of developing tailored agreements (maatwerkafspraken) to facilitate collaboration (Ministerie van Economische Zaken en Klimaat, 2024).

The institutional theory provides a framework for understanding how public-private partnerships (PPP) are shaped by the institutional environment (Scott, 1995). The following principles from the institutional theory framework are foundational to the development of tailored agreements:

- **Legitimacy and institutional norms:** the development of tailored agreements is essential to address specific societal norms and stakeholder needs, increasing legitimacy. It can be seen as an effort to meet the diverse expectations of public institutions and private actors, which aligns with institutional pressures to balance public good with efficiency.

- **Flexibility within rules:** institutional theory stimulates that organisations may adopt formal structures or agreements to comply with regulatory and/or normative pressures while allowing flexibility. Tailored agreements can address gaps by establishing project-specific frameworks to incentivise actors and make progress in transitions.
- **Institutional isomorphism:** actors active in the hydrogen transition will mimic successful examples, follow professional standards, and comply with public authority requirements when the tailored agreements are effective and have positive results.
- **Cultural-cognitive influences:** the institutional theory underscores the importance of shared cultural and cognitive understanding. Via the development of tailored agreements, this understanding will potentially develop.
- **Path dependency and institutional change:** historical institutional arrangements shape the design of tailored agreements, reinforcing existing practices and expectations. However, institutional entrepreneurs (industries that have the intrinsic motivation to develop [#44]) drive change by introducing innovative agreements that address unique challenges and help evolve established norms.

According to the development of the tailored agreements is the following [#31][#47]: the approach integrates strict climate goals with flexibility and support through phased agreements such as the Expression of Principles (EoP) and Joint Letter of Intent (JLoI), progressing towards binding commitments between industry and government. It emphasizes assessing the feasibility, efficiency, and potential of industries to contribute significantly to sustainability objectives. Hydrogen plays a pivotal role in these agreements, aiming to accelerate the broader energy transition while safeguarding the competitiveness and sustainability of the Dutch industry (Ministerie van Economische Zaken en Klimaat, 2024).

Instead of creating this shared vision, the governmental regulators remain stuck in reacting to market failures with specific subsidies and regulations. Companies act opportunistically, only pursuing projects with an immediately viable business case, resulting in fragmentation and a lack of consistency. This pattern traps us in stagnation, while a mission-driven approach could make all the difference (Kirchherr, Hartley, and Tukker, 2023). The design of these tailored agreements (maatwerkafspraken) is currently under discussion and is expected to be completed by the end of 2025. The current steps align with institutional developments and highlight the importance of mutual understanding in creating agreements that support both the hydrogen transition and industry growth in the Netherlands.

7.2. Building blocks for supply chain development

The findings reveal an imbalance in terms of support for developments at the supply chain's front end compared to the supply chain's back end. This allocation is rather good for incentivising market development and making sure hydrogen can be produced. However, the back end of the supply chain needs to ultimately pay for the price of hydrogen [#44], including the price for the developed electrolysers, transportation and among others the high green electricity price [#7][#41]. Changing a process that allows back-end industries like steel production to make use of hydrogen will result in prices that are too high due to unfavourable market conditions. The origin of the mistake in pricing conditions can be found in wrong predictions [#32]. This might be a reason why governments focussed much on the development of the front end of the supply chain.
The problem that developed, as highlighted in the market development regulatory void, exists foremost out of two parts:

- Back-end industries do not make investment decisions in line with hydrogen development.
- Developed electrolysers are not able to be implemented, while readily produced, not allowing for further development.

Various stakeholders therefore emphasise the need for the reallocation of resources more focused towards the back end of the supply or developing new supporting mechanisms (subsidies) that are focussed on making FIDs at the back end of the supply chain. The principles of the economies of scale can be applied here to support the development of the supply chain.

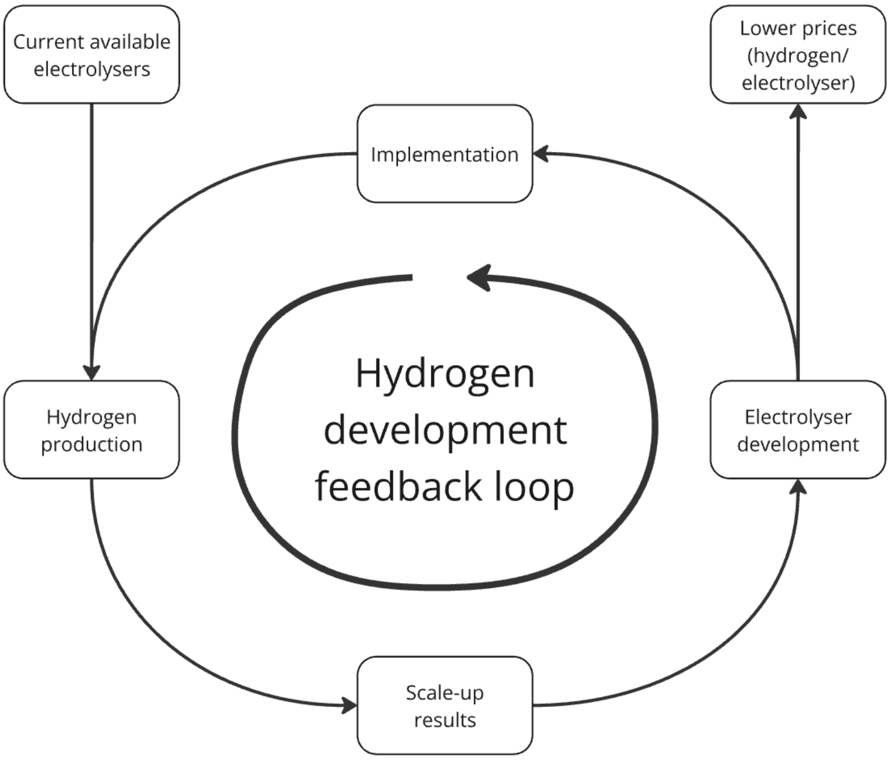

Figure 7.1: Feedback loop for electrolyser development in the hydrogen transition (made by author).

7.2.1. Economies of scale to reduce production costs

The principles of the economies of scale can address the dis-balance that exists (George J. Stigler, 1958b). By focussing on the creation of a feedback loop where increased adoption and production must lead to reduced costs for the price of hydrogen and electrolysers (Sundkvist, Milestad, and Jansson, 2005). Figure 7.1 describes a simplified method of applying this feedback loop regarding the hydrogen transition.

As more industries at the back end of the supply chain (e.g., steel production) adopt hydrogen within their processes, demand increases, driving large-scale production and reducing the unit cost of hydrogen and related technologies. To support this transition, governments (EU or NL) can introduce targeted subsidies or incentives to offset the high initial development and implementation costs (Takalo, Tanayama, and Toivanen, 2013). Measures such as funding process adaptations or offering tax benefits for hydrogen utilisation would help mitigate investment risks and facilitate Final Investment Decisions. Over time, the learning curve within the development cycle will enhance efficiency and adaptation, further lowering costs. Establishing institutionalised feedback loops, where governments and industries regularly evaluate and adjust subsidies and support mechanisms, will ensure sustained progress
The growing market will incentivise further innovation and cost reductions, with the ultimate goal to create a self-sustaining system. For the hydrogen case, this means ensuring that resource allocation supports both production and consumption, facilitating a market where hydrogen adoption becomes scalable and self-sustaining.

7.2.2. Sector coupling

By integrating energy-intensive industries, the creation of clusters can lower the barriers to the adoption of hydrogen in the system. Creating a more stable and diversified demand for hydrogen can be from local industries to bigger industries that work together towards a sustainable solution. Due to the connection of clusters (Van Nuffel, 2018), electrolysers can be used consistently (switching on and off does not work (Haleem et al., 2022)), reducing costs (investment, production, operation) creating a more secure investment environment. In addition, locally coupled sectors could share infrastructure, pipelines, storage and distribution networks [#5]. Linking networks will lower the cost of infrastructure development. Shared infrastructure thereby promotes collaborative environments that enhance the scaling up of hydrogen ecosystems.

7.3. Addressing governmental structures to allow progress

The interview transcripts and findings indicate that stakeholders frequently refer to complex governmental structures. Stakeholders emphasise that it is: ‘a small circus of schemes’ [#30] developed at various levels of governance. The institutional theory highlights the need for regulatory clarity. In addition, certain stakeholders mentioned in the findings that there is a principal-agent problem that slows down the development infrastructure [#9][#10]. Both will be addressed in the sections below.

The literature highlights that the regulator’s role is not necessarily to actively drive technological developments, such as scaling up, but rather to create the conditions that enable progress (OECD, 2020). Often, in the case of the hydrogen transition as well, the role of the regulator is taken by governments active at various levels (multi-level governance). Uncertainty in these conditions can lead to procrastination among industry actors, delaying progress. However, once a stable regulatory environment is in place, it is up to industry players to adopt the technology and enable scale-up within these provided conditions. The following parts will elaborate on the current uncertainty within the conditions that are currently set by regulators.

7.3.1. Regulatory development, standards, and level playing field

Regulations that apply to the hydrogen transition are predominantly for Dutch stakeholders developed at two levels: European and national. Government officials interviewed argue [#4] that it is an enormous puzzle to be able to align the regulations and navigate the complex landscape. An Expert [#6] argues that the current developments on the national level and European levels create a landscape of competing interest, where parties are insecure about what is considered to be relevant. The conventional approach dictates that the EU sets overarching goals and regulatory frameworks, which are then adapted by the Netherlands to fit national circumstances. National subsidies are often linked to EU funding or mechanisms such as IPCEI (Rijksdienst voor ondernemend Nederland, 2024). The institutional theory addresses the challenges of multi-level regulations and subsidies by promoting the development of shared norms and standards (Scott, 1995). Establishing committees to facilitate communication and alignment between the EU, the Netherlands, and industry stakeholders, such as steel plants, can enhance coordination. Additionally, incorporating feedback loops to identify and address misalignments is essential (Georgiadis and Besiou, 2014). When designing subsidies and regulations, involving stakeholders from diverse backgrounds can contribute to more practical and effective policy development.

Cross-border standards:
In addition to challenges in subsidy and regulatory development, infrastructure development faces issues related to standardisation, leading to cross-border conflicts. For example, Germany and the Netherlands base standards for hydrogen pipelines on different principles [#20], making cross-border interaction more difficult. The hydrogen backbone cannot be developed without cross-border interactions, incentivise the development of uniform standards that are effective at an EU level.
Currently, there is no existing cross-border hydrogen pipeline in Europe, the current goal is to develop the market and to emphasise the need for hydrogen transportation to connect clusters. The current modus is thus very explorative with a certain urge to develop the infrastructure. When wanting to develop infrastructure based on European standards, the process will be drastically slowed down. All countries involved need to agree on these standards; while foremost Eastern European countries have not really started this transition; making it a much slower process. Thereby, the real technical bottlenecks are identified and are currently explored, like pressure and purity, and are hard to make standards for while having multiple unknowns (DNV, 2020):

- **EU development:** provides large-scale coordination, funding, and interoperability, but it can be slow, complex, and less adaptable to local needs.
- **National development:** allows for flexibility and faster execution but risks fragmentation and lower alignment with cross-border goals.

When first technical issues are covered in a later stage, it is essential to create EU standards and guidelines for hydrogen development to provide greater security and support.

This development of cross-border standards can be related to the theory of self-regulation versus strictly regulated (Marchant, 2011a). National standards development can be related to self-regulation, and more development speed for national infrastructure but lacking international application possibilities. Developing at a European level will be slower because countries all need to agree independently with the standards. This results however in internationally acknowledged standards on which basis can be developed, making transnational networks easier implemented.

Level playing field:
As the findings underscore the need for the development of a level playing field, it is important to take away uncertainties for investments that need to be made [#23]. A level playing field is the creation of equal conditions, equal market potential and competition, and requirements (Kapstein, 2010). Currently, there are numerous differences that result in postponement of investment. Across the world, there are better conditions compared to other locations in the world, not just naturally, but also created environments by governments. For example, the Chinese government subsidises the production of electrolysers massively and will create the hydrogen market when needed. More closely there are also differences between countries, it is more expensive to connect electrolysers to the grid in the Netherlands compared to Germany [#25]. These 'unequal' conditions make stakeholders take the wait-and-see approach [#35], lacking the hydrogen adaption possibilities.
A level playing field fosters fair competition, driving innovation within the Dutch market. When applied across borders, it promotes a more cohesive environment that stimulates economic and technological progress. The following mechanisms support the establishment of a level playing field (European Commission, n.d.):

- **The ETS-price (CO2 price):** is not a proactive market mechanism that provides for example subsidies, it helps to create equality over the entire world, so all industries need to pay the same price for the production of CO2 (Emissieautoriteit, 2022).
- **Harmonising standards and policies:** across countries can establish consistent transnational regulations, fostering fair competition and enabling effective collaboration.
- **Balancing costs and incentives:** by aligning green hydrogen prices and availability can reduce the incentive for industries to relocate.
- **Supporting local development through targeted subsidies and incentives:** can help offset higher costs in stricter regulatory environments, encouraging industries to remain local while adhering to robust environmental standards.

Establishing a level playing field beyond Europe can be complex, but within Europe, it is crucial to address these challenges and ensure equal opportunities. The risks and benefits for hydrogen developers in Germany and the Netherlands should be balanced, preventing location-based differences. At this stage of the hydrogen transition, the focus should not be on differences in the cost of building electrolysers but rather on their optimal placement to maximise benefits for the transition.

7.3.2. Addressing the principal-agent problem

The last point of discussion is related to the principal-agent problem; the findings made clear that progress is slowed down due to inefficient governmental structure that does not incentivise the creation of the infrastructure [#9][#10]. By appointing a single institution to the creation of the infrastructure (the Gasunie), the speed of implementation is determined by this entity, having a monopoly. The principal in this case is the ministry of KGG, they want the hydrogen adaption to be as efficient as possible. The Gasunie (agent) can develop the infrastructure at their own pace, resulting in the best financial returns for example. At a certain point, the Gasunie needs to get the investment in the hydrogen infrastructure back, they are a semi-government (Duivenboden et al., 2019). While KGG wants a fast transition (Nationaal Waterstof Programma, 2024a), Gasunie may maximise returns and will therefore develop at their optimal speed, having the monopoly passion and the know-how, they could slow down the hydrogen infrastructure implementation drastically. To address this principal-agent problem, the following actions can be relevant according to the institutional theory and the creation of trust and legitimacy:

- **Align incentives:** by creating performance-based contracts: milestones or deadlines.
- **Share the financial risk:** to accelerate the implementation, financial support can be provided.
- **Stimulation of transparency:** frequently reporting the progress. An option can be that there is an additional government body that checks whether the progress of Gasunie is in line with the needs of stakeholders (supply and demand) that are in need of hydrogen infrastructure implementation.
- **Alternative transport:** to create the first hydrogen transportation options, alternatives to pipelines can be shipping or train transport (point to point).

The last action is underscored by various stakeholders [#35][#51] to create market development and to make transportation feasible. KGG aims to scale up electrolyser capacity in the Netherlands through the refinery route, hoping to ensure sufficient availability of renewable hydrogen in the long term [#19] (Rijksdienst voor Ondernemend Nederland, 2025; Nationaal Waterstof Programma, 2024b).

7.4. Evaluating the institutional theory against empirical findings

This section will provide a brief overview of the institutional theory in combination with the findings. Figure 7.2 present both processes that are part of the institutional theory and regulatory voids found in the hydrogen transition. The goal of this figure is to present the reader with an overview of which parts of the processes from the institutional theory are covered within the two regulatory voids[2].

	Regulative			Normative			Cultural-cognitive		
	Rules and regulations	Regulatory selection pressure	Regulatory adaptive capacity	Standards and norms	Normative selection pressure	Normative adaptive capacity	Shared understanding	Cultural-cognitive selection pressure	Cultural-cognitive adaptive capacity
Void: MD	Y	~	Y	N	~	~	Y		
Void: ID	~	~	Y	~	N	~	Y		

Y = yes; N = no; ~ = partly; [empty] = no relation found

Figure 7.2: Overview whether institutional processes are applied to the identified regulatory voids.

As becomes clear in the findings and discussion, both the identified regulatory voids predominantly lack development in normative processes. These processes are essential to steer technology development and necessary for making progress. This underdevelopment must be addressed by both the government at the national and international levels, as well as by industry parties. Providing clarity from both public and private perspectives on constraints, needs, and objectives will create insight and the ability to address regulatory voids more effectively.

7.4.1. Market development evaluation

Figure 7.2 tries to illustrate the connection between the identified market development void and the processes from the institutional theory (Scott, 1995). Shortly the different process and the explanation behind the construction of the figure will be done.

- **Regulative process:**
  Regarding regulatory development, the interview transcripts and case study reveal that numerous regulatory mechanisms are already in place. However, these regulations are primarily concentrated at the front end of the supply chain. In contrast, the back end of the supply chain remains under-regulated, with a lack of clear policies and supporting schemes, which creates uncertainty for industries considering investment decisions. From the perspective of

[2]To clarify: 'N' implies that no relation is found; '[empty]' implies that the relation is not investigated (out of scope).

the regulative pillar, the absence of well-defined rules, enforcement mechanisms, and financial incentives results in underdeveloped institutional pressure on industries to commit to investments. Regulatory voids in this segment of the supply chain limit coercive pressures, while normative expectations and mimetic behaviours are insufficient to drive decision-making. Furthermore, without clear enforcement or incentives such as subsidies or a level playing field, industries remain argumentation to potentially relocate operations with more favourable conditions. This regulatory uncertainty hampers long-term strategic commitments and slows down the transition process.

- **Normative process:**
  The analysis of the interview transcripts, combined with insights from the literature, indicates that the normative processes essential for market development remain largely underdeveloped or absent. The lack of (widely) accepted standards for market mechanisms reflects the limited adoption of hydrogen, preventing the emergence of shared expectations and industry norms. From the perspective of the normative pillar of institutional theory, the absence of established professional standards, best practices, and sector-wide norms contributes to market uncertainty and slows development speed. Stakeholders highlight key gaps, such as the lack of standardisation in hydrogen purity levels, handling procedures in contracts, and the classification of market mechanisms. Without these normative frameworks, industries struggle to align their operations, negotiate agreements, or establish trust in market transactions. Therefore both public and private parties must express their needs to emphasise clear, suitable and adaptive norms.
- **Cultural-cognitive process:**
  Regarding the cultural-cognitive processes of institutional theory, the stakeholder groups demonstrate a shared understanding of the transition towards a sustainable energy system, with hydrogen playing a critical role. Interviewed stakeholders recognise the necessity of change and are actively exploring the best implementation strategies. The rest of this process is out of scope.

7.4.2. Infrastructure development evaluation

Likewise, as for the market development void, the infrastructure development void will be shortly explained regarding the relations illustrated in Figure 7.2.

- **Regulative process:**
  Regarding the regulatory development for infrastructure, stakeholders emphasise that current regulatory frameworks are primarily based on the Dutch Natural Gas Directive. However, the regulatory process for hydrogen infrastructure is currently focused on national development, despite the need for cross-border regulations to facilitate transnational transportation. From the perspective of institutional theory's regulative processes, primary regulatory developments currently concern the safety and operational requirements for hydrogen transportation. While initial steps have been taken to establish regulations for pipeline infrastructure, alternative transport methods—such as hydrogen transport via ships, rail, and road—remain underdeveloped, fragmented, and lacking in harmonised standards. Furthermore, monitoring and enforcement mechanisms for hydrogen transportation remain poorly defined, creating uncertainty for market stakeholders who rely on clear infrastructure development plans. The lack of regulatory oversight and enforcement presents challenges in ensuring compliance and managing risks effectively. Closing these gaps through coordinated national and international regulatory frameworks will be crucial for establishing a safe and efficient hydrogen transport network.
- **Normative process:**
  The norms and standards for hydrogen infrastructure development are not yet at the level required to support a fully operational and scalable system. From the perspective of the normative processes of institutional theory, there is a lack of consensus on key technical aspects. One of the areas of uncertainty concerns for example hydrogen purity. Stakeholders across the hydrogen supply chain, both producers and consumers, continue to debate the required purity levels, as no universally accepted standard has been established. Similarly, operating pressure within hydrogen infrastructure lacks standardisation, creating further technical and regulatory ambiguity. Beyond pipeline infrastructure, the absence of established standards for alternative transport methods (such as rail and maritime transport) further complicates the development of a coherent hydrogen network. For instance, uncertainty persists regarding hydrogen transportation

by train, particularly along the refinery route in the Netherlands, as well as the feasibility and safety protocols for hydrogen shipping. While efforts have been made to incentivise alternative transport methods (such as the correction factor of 0.4 introduced by Ministerie van Klimaat en Groene Groei (2024)) the lack of well-defined technical and operational standards continues to hinder their large-scale implementation. To advance hydrogen infrastructure development, normative alignment among stakeholders is essential. This includes harmonising technical standards, fostering industry-wide best practices, and ensuring regulatory bodies collaborate with industry actors to establish clear and enforceable norms (public-private partnerships).

- **Cultural-cognitive process:**
  Similar to the market development void, the advancement of hydrogen infrastructure is impeded by uncertainty and a lack of clear standards and regulations. Key players, such as Gasunie (holding the pipeline development monopoly in the Netherlands) acknowledge the pressure to progress but remain hesitant about the best course of action. The absence of a shared vision further hampers progress, as stakeholders struggle to align their strategies. Until clear standards and common frameworks are established, infrastructure development will likely remain fragmented and uncertain.

7.5. Limitations and future research

This sub-section of the discussion chapter addresses the limitations of the research and provides recommendations for future studies. It begins by outlining the limitations of this research, followed by suggestions for future research aimed at academics and stakeholders interested in (hydrogen) transitions concerning the emergence of regulatory voids.

7.5.1. Limitations of the research

The limitations of this research will be discussed by evaluating the applied research methodology, data collection methods (case study and interviews), and the analysis and representation of findings.

The hydrogen transition, and the broader energy transition, is a complex challenge that cannot be resolved quickly or easily. It is potentially one of the most complex transitions that the world has ever faced. This research tries to contribute by providing insights into how the current challenges, specifically the regulatory voids identified, can be adequately addressed. This was achieved by independently interviewing various stakeholder groups affected by these voids (20 interviews conducted in total). However, when situating this research within the broader timeline of hydrogen as a potential solution for the energy transition, it represents only a small fragment: a single frame from a long movie. A key limitation of this research is the inability to consider the entire timeline of hydrogen adoption.
Consequently, it cannot fully account for decisions that influence progress and adaptation over time, made before, during or after this research. This study aims to validate whether current strategies and approaches align with theoretical ideals and proposes a pathway to address regulatory voids: bottlenecks that need guidance to move forward or otherwise limit the progress speed of the transition. While this research tries to explore both a technically oriented infrastructure void and a market void to gain a holistic view; each regulatory void is unique. Each void requires a specific, tailored approach, often not pre-existing, as its absence has been a barrier to project progress.

This study employed the Gioia methodology to analyse qualitative data, which is particularly effective for generating insights and identifying patterns through first- and second order terms. However, the approach is not without its limitations, like:

- **Risk of oversimplification:** the Gioia methodology may oversimplify the complexity of data, potentially resulting in the loss of information during the categorisation step. To mitigate this risk, detailed notes were taken during interviews, and notable quotes from interviewees were highlighted separately.
- **Risk of confirmation bias:** researchers may prioritise data that fits within their analysis framework or theoretical lens. This could lead to selective coding and analysis. A parallel approach (using a secondary method of data analysis) could help validate the identified patterns and reduce this bias.

By addressing these methodological limitations and exploring alternative approaches, future research could build on this study's findings to provide even greater insights into the hydrogen transition and its regulatory challenges.

7.5.2. Recommendations for future research

In this subsection, recommendations for future research are proposed and described. Based on the limitations and the findings of this study, several fields of study are suggested:

- **Change in theoretical lens/scope:** this research applied institutional theory to assess whether regulatory voids can be effectively addressed. While this theoretical lens provided valuable insights, a follow-up study is highly recommended to explore whether alternative theories might offer a more suitable approach. Regulatory voids often have unique, context-specific characteristics that may be better addressed through different or complementary theoretical frameworks. Incorporating multiple theories or alternative perspectives could enrich the understanding of regulatory voids and provide a more comprehensive approach to managing them effectively.
- **Multiple case study approach:** this study employed a single exploratory case study to identify regulatory voids within the hydrogen transition. While this case offered broad insights into the overarching challenges of the transition, including smaller, focused case studies could potentially add significant value. To clarify, future research could for example examine specific instances that undermine the trust and legitimacy principles. In addition, a more targeted case study could investigate the effects of delays, such as those associated with the DRC, related to implementation speed and stakeholder engagement. Comparing these dynamics across different transitions would offer valuable insights into the interplay between trust, stakeholder collaboration, and regulatory development.
- **Focus regulatory void development to R&D stage of technology development cycle:** this research is focused on regulatory voids that are emerging in the diffusion stage of the technology development cycle. As already introduced in the literature, Section 2.2.1, there is another stage within the development cycle where regulatory voids are likely to emerge: the R&D stage. It is recommended to conduct research regarding the alignment of technology developments and whether they align with other transitions to see if regulatory voids can be prevented. On the other side, it can be interesting to see if technologies can be effectively supported, so they are able to develop. Investigating situations in which the regulatory capacity is not a restricting factor, but technology developments instead (like technology development related to CCS for example (G. C. Institute, 2023)).
- **Include more themes within the energy transition:** lastly, this research focuses on adequately addressing regulatory voids within the context of the hydrogen transition. The proposed process interventions and findings may differ for other transitions that involve various contexts or characteristics. Researching other transitions and comparing the findings, discussions, and conclusions would be of great value. Such comparisons could provide greater insight into how regulatory voids can be effectively addressed in varying scenarios and prove the insight gained from these insights.

Future research can provide a comprehensive understanding of the applicability of the institutional theory, the way regulatory voids emerge and how they can be adequately addressed.

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8
Conclusion

This research seeks to effectively address the emergence of regulatory voids in the diffusion stage of transitions. It explores the conceptual background, defines regulatory voids, and examines relevant theories for addressing them. To evaluate whether these theories actively mitigate regulatory voids, the study focuses on an ongoing transition: the hydrogen transition. Through primary data collection, including a case study and stakeholder interviews, this research aims to provide guidance and theoretical validation for researchers and professionals navigating regulatory voids in transitions.

The primary objective of this research was to address the main research question, supported by four sub-questions, each contributing to its resolution. These questions were introduced in Section 1.3.1 and will be systematically answered in the following subsections. Through a comprehensive literature review, data collection via a case study and interviews, and subsequent data analysis, a holistic understanding is developed to answer the following main question:

"How can regulatory voids be adequately addressed concerning developing technologies related to hydrogen adoption in the Netherlands?"

8.1. Answering: sub-research questions

To provide an answer to the main question, the sub-questions will first be answered individually. These individual answers will be integrated to deliver a complete answer to the main research question at the end of this section.

8.1.1. RQ 1: What can be done to effectively address regulatory voids?

Through literature review, the state-of-the-art knowledge on regulatory voids was summarised, providing insights into what scholars have discovered and developed. This review highlights the relevance of this research by contextualising it within the existing academic literature. The literature review is divided into three sections to address this sub-question: the concept and definition of regulatory voids, the appearance of regulatory voids, and strategies for effectively addressing regulatory voids.

Conceptual understanding and definition of regulatory voids:
The development of innovative technologies within transitions is not introduced from one day to another. As technologies develop, regulations must adapt to validate and accommodate new technology developments. Technology innovations are often complex and not clearly defined, making it difficult to set conditions and align regulations. This misalignment often results in regulations lagging behind the pace of technological development progress. While regulations must protect society from potential risks and harmful situations, ensuring the safe development of new technologies in advance becomes particularly challenging. For technologies viewed as extensive, open-ended social-technical systems, local variations and unpredictable behaviours further complicate the establishment of effective regulatory norms (Wynne, 1988).

In the context where technological advancement (often) outpaces the establishment of regulatory development, a figuratively 'gap' emerges, better known as: the regulatory void. This void represents the absence of clear guidance on how to address the regulatory needs of technology development in transitions. The term "regulatory void", is therefore defined the following way (Wynne, 1988):

“A situation in which existing legislation and regulatory frameworks fail to adequately address or cover a specific issue, activity, or area. The absence of existing laws, regulations, or guidelines can result in ambiguity, uncertainty, and potential misuse or abuse of the situation that is created.”

As the definition of the regulatory voids expresses the inability of regulatory institutions to adequately steer technology developments can result in an unsafe situation and a process that is slowed down. Here the ’pacing problem’ highlights the increased disconnection between the technology advancements and the slower pace at which regulations are developed (Marchant, 2011a). This pacing problem not only contributes to the appearance of regulatory voids; but also emphasises the evolving nature of these gaps: the void can grow when not adequately addressed.
When no specific regulations apply to technological development, self-regulation allows industries to innovate while aligning with public goals (Marchant, 2011b; Wynne, 1988). In contrast, a strictly regulated environment prioritises safety but can affect the pace and progress of technological developments. To address this challenge, adaptive regulations can be implemented to manage technological developments more effectively (Pahl-Wostl, 2009). By balancing flexibility and control, adaptive regulations help to minimise regulatory voids.

Regulatory void appearance: diffusion stage
The second part examines the most critical and frequent occurrence of regulatory voids in transitions. To provide context, the technology development cycle is introduced (Foxon, 2005). The technology development cycle outlines five unique stages that technological innovations undergo before becoming fully integrated into society and/or industry. In relation to the emergence of regulatory voids and their impact on the pace of development in transitions, the diffusion stage is identified as particularly critical and relevant for this study.

Diffusion Stage:
In the diffusion stage, regulatory voids emerge when technologies are proven to be viable but fail to align with existing regulatory frameworks, preventing their adoption by the market. As a result, they struggle to integrate into the future market thus limiting development progress. Developing and/or changing regulation is often a slow process, hindering the adoption (Lescrauwaet et al., 2022). The regulatory void in the diffusion stage can be re-defined:

”When existing regulations fail to align with the requirements of a mature technology. Rather than an absence of regulation, these voids arise from outdated, fragmented, misaligned, or inconsistent rules and standards; leading to uncertainty, market barriers, and delays in technology deployment.”

The readiness of the technology at this stage implies that market adoption is crucial for further development. While the technology itself is mature, its large-scale implementation often lacks momentum due to regulatory uncertainties and market hesitancy. A key challenge arises when regulatory frameworks are not yet fully established, creating uncertainty that discourages industry actors from investing in technologies to allow scaling up. To break this cycle, economies of scale can play a critical role by reducing costs through increased production capacity (George J Stigler, 1958a). However, regulators should focus on setting clear conditions and removing uncertainties rather than directly driving market adoption. Without a stable regulatory environment and predictable economic conditions, achieving economies of scale remains challenging.

Strategies for addressing regulatory voids:
Regarding transitions, the institutional theory provides an interesting framework to address regulatory voids. Via a framework that focuses on the interplay between regulative, normative and cultural-cognitive processes, regulatory voids can potentially be more adequately addressed. The institutional theory highlights how institutions shape and are shaped by society, organisation, and social systems, to offer a nuanced and inclusive approach to manage technology developments in transitions.

Regulatory voids emerge due to the misalignment between (rapid) technological advancements and slower regulatory processes. The institutional theory addresses this by introducing mechanisms that guide behaviour and decision-making through shared norms, rules, and cultural beliefs (Scott, 1995):

- **Regulatory processes:** the creation of enforcing formal rules, regulations and laws to guide behaviour, ensure compliance and support safe and structured development.

- **Normative processes:** establishment of standards, shared values, and acceptable behaviours. Crucial for emerging technology diffusion, aligning stakeholders, promoting knowledge sharing and increasing legitimacy (Jeong and Kim, 2019).
- **Cultural-cognitive processes:** creating shared beliefs and assumptions. Having an effect on the way technologies are understood and adopted (integration into society).

The institutional theory can effectively address regulatory voids by emphasising legitimacy, creating shared practices, and integrating adaptive mechanisms. Technology developments in the diffusion stage, especially underscore the importance of normative processes in establishing certainty and standards, providing that emerging technologies can be more successfully adopted. This exhaustive approach offers valuable insights for shaping regulatory frameworks that address regulatory voids adequately and thus promote technological transitions.

8.1.2. RQ 2: What is the status quo of the hydrogen technology development?

This part of the research is primarily addressed through a case study on the implementation of hydrogen: Hy3+ (HY3+, 2024). In addition, the regulatory voids identified in the case study are validated in the initial phase of each interview, as outlined in the interview protocol (Appendix B).

Hydrogen technology has obtained significant momentum in recent years and has become a key development for future sustainable energy systems. Hydrogen has become of great value for the energy transition, gaining worldwide attention and resulting in the fact that new regulations and future visions are dedicated to this development. Despite the growing attention and the advancements in technical capabilities of hydrogen that are made, the adoption of hydrogen infrastructure, and insecurities in the market remain underdeveloped. This results in stagnation, primarily in the diffusion stage of the technology development cycle, while hydrogen holds much future value and potential. The Hy3+ project highlights various critical bottlenecks, which are rooted in two overarching regulatory voids (HY3+, 2024):

- **Regulatory void: market development:**
  This void highlights the absence or underdevelopment of the hydrogen market, leading to a loss of momentum in implementing advanced hydrogen technologies. Despite heavy subsidies and the readiness of technologies like electrolysers, the lack of demand stagnates their adoption by the industry, ultimately slowing the pace of hydrogen technology development and the hydrogen transition in general.
- **Regulatory void: infrastructure development:**
  A critical step in enabling hydrogen transport is the development of hydrogen infrastructure. Delays and absence of development in this area leave hydrogen industry stakeholders waiting, significantly impacting the development speed of the hydrogen transition. Clear regulatory guidance and established norms are highly needed to support and accelerate progress.

The absence of critical infrastructure and delays in essential projects like the Delta Rhine Corridor (DRC) are causing stagnation in hydrogen development (in the Netherlands). To emphasise, the only industrial cluster that announced significant hydrogen uptake in the next few years is the Rhine-Ruhr (Germany). Due to delays, it is unlikely to be efficiently connected to Rotterdam and allow market creation.

The current state of hydrogen technology development highlights the need for coordinated regulation, infrastructure investment, and market mechanisms. Without addressing these barriers, the diffusion of hydrogen technologies will continue to face significant challenges. This inevitably leads to delays in integration into the energy system and hinders contributions to the energy transition.

8.1.3. RQ 3: What are effective strategies on how regulatory voids can be overcome?

When analysing the effectiveness of developing hydrogen technologies and adequately addressing the regulatory voids, key aspects from the various interviewed stakeholder groups emerged. The following aspects describe what is lacking and what are effective strategies.

Strategies addressing regulatory void: market development:

- **Allocation of resources over the supply chain:** to address the wait-and-see approach from the back end of the supply, incentivising the hydrogen-consuming industries via targeted subsidies or tax benefits will reduce investment risks. Balancing the supply chain from production to consumption will help to create an equal distribution The back end of the supply chain has to deal with fewer investment risks and will contribute to the hydrogen transition.
- **Trust and transparency creation:** current delays and historical occasions have resulted in limited trust between governments and industries. (Re)building trust between these through consistent, long-term policy frameworks, avoiding abrupt changes or delays in announced plans and creating cooperation is essential to make progress. This will not only have a positive effect on this transition but also on future transitions that rely on the developed trust.
- **Public-private initiatives:** tailored agreements (maatwerkafspraken): having an effect on building the trust relation as well; strengthen the public-private partnerships through customised agreements with the industry-specific needs to incentivise the up-take of hydrogen. Maatwerkafspraken helps government institutions to allocate where most hydrogen potential is among the back-end of the supply chain to incentivise the first uptake of hydrogen effectively.
- **Regulatory clarity:** develop regulations and subsidies that are clearly defined so stakeholders know what the conditions are and what is applicable. Creating guidelines at a national level is essential to make goals more tangible for stakeholders compared to EU-level targets.
- **Allow for scale-up:** current technologies, such as electrolysers, face implementation challenges due to regulatory uncertainty and market limitations, restricting the scale-up of the hydrogen supply chain. Clear and consistent regulatory conditions are necessary to provide certainty for investment, allowing economies of scale to drive price reductions. The technology development loop can gain momentum once the regulatory environment stabilises and market actors respond.

Strategies addressing regulatory void: infrastructure development:

- Development of European standards: establishing standards to facilitate the construction of European hydrogen pipelines is essential for progress and fostering unity among countries. Existing national standards show differences that complicate cross-border collaboration. Addressing these challenges can serve as a foundation for creating unified European standards.
- Allow for alternatives: due to the absence of current infrastructure, alternatives must be explored to facilitate the transportation of hydrogen. Point-to-point connections via inland shipping or train can be essential to reach hydrogen clusters. Dutch national government should support alternative routes to incentivise the market by connecting production and demand.
- Address principal-agent problem: the current government structure can become more effective, creating incentives for the Gasunie to develop infrastructure more quickly. Taking away financial issues, creating development incentives, or creating more information transparency will help to speed up the hydrogen infrastructure production.
- Coordination between TSOs: creating collaboration between the infrastructure planners (Gasunie and TenneT) will result in faster developments. When cooperation is not possible, prioritise infrastructural needs and decisions. Coordination between TSOs from various countries is highly needed to make sure infrastructure developments can be connected at cross-border locations.

Overarching themes for addressing the regulatory voids:

- Mission-driven approach: instead of addressing the failures and shortcomings of market mechanisms, such as initiating the implementation of electrolysers through regulations and subsidies. This involves the creation of collaboration between public and private stakeholders to establish clear visions and long-term goals. In addition, it emphasises addressing current challenges while keeping an adaptive mindset to navigate future obstacles effectively together.
- Allow technology development: the creation of the technologies is foundational for transitions to progress. When in-country developed technologies are not able to be implemented, market development will be lacking, and industries tend to move or import technologies. Having a negative effect on the overall creation of stimulating future technologies.

- Align economic and environmental goals: Balance public (societal) and private interests through policies that simultaneously promote sustainability and maintain industrial competitiveness across the supply chain. Establishing a level playing field within Europe is crucial for creating a more equal investment climate, ensuring decisions are based on the most favourable locations for sustainable development.

8.1.4. RQ 4: How can the identified processes obtained from the hydrogen transition be used to address regulatory voids in general?

The emerged regulatory voids within the hydrogen transition create an insightful understanding for addressing them to their wide applicability. Especially processes in transitions that are related to the technological and infrastructural contexts are relevant due to the relation with adaptability, stakeholder collaboration, and regulatory clarity with guiding support. The following key takeaways are outlined:

- **Trust and legitimacy:** trust among stakeholders is considered to be an essential building block to create sound and effective processes. Alignment of all parties involved is essential to enable cohesive and collaborative decision-making in order to support transitions. Regulatory voids develop due to the existence of a knowledge gap, stakeholders are not on the same page. Resulting in the absence of supporting mechanisms for the highly needed technologies to be able to develop. When trust is absent, legitimacy becomes questionable leading to technologies not being applied.
- **Clear and adaptable regulations:** develop regulations that balance adaptability with clarity, providing stakeholders with both certainty and flexibility. Despite the fact that adaptable regulations may sometimes lack specificity; they are essential for accommodating technology development in transitions, especially since transitions have often an international scope. Aligning regulations with the standards of the countries involved; will support cross-border applicability for technology-driven industries. Similarly, establishing transnational standards provides alignment across borders, facilitating smoother transitions.
- **Guidance to achieve long-term goals:** streamline standards, regulations and subsidies supported by governmental guidance is essential. Emphasising the need for early stakeholder adaption to clarify (long-term) visions and goals along the entire supply chain. Early identification of market needs is key to creating applicable policies that are generally supported by both industries and governments.
- **Enable scalability in diffusion stage:** when formulating regulations and economic incentives, it is crucial to create a stable and predictable framework that supports market development and enables scaling through industry engagement and investment. A well-structured regulatory environment should also prioritise supply chain coordination, ensuring a balanced interplay between production and consumption. By eliminating regulatory uncertainties, enhancing supply chain integration, and ensuring economic viability, regulations can facilitate favourable conditions for the hydrogen sector to expand efficiently through market-driven growth. In this way, scale-up by the industry parties over the entire supply chain is more provided.

In addressing regulatory voids during the diffusion stage, regulators should not be viewed as active drivers of scaling up but rather as facilitators of the necessary conditions for industries to operate effectively. Their role is to establish clear, stable, and adaptable regulatory frameworks, minimise uncertainty, and create an environment where private sector actors can confidently invest and innovate. By prioritising regulatory clarity, standardisation, and facilitation, regulators from various levels can support a structured, safe, and more efficient transition across emerging industries.

8.2. Answering: main research question

The previous section individually addresses the four sub-questions. This research makes several important contributions, both practical and academic. Primarily, it identifies the current state of the hydrogen transition by pinpointing active regulatory voids and assessing whether they can be addressed using the institutional theory framework (Scott, 1995). To further contribute to the understanding of adequately addressing regulatory voids, the following research question is answered:

"How can regulatory voids be adequately addressed concerning developing technologies related to hydrogen adoption in the Netherlands?"

To effectively address regulatory voids, it is key to understand the context in which these voids develop. The insecure and complex nature of transitions results in difficult stakeholder interactions and fragmented market mechanisms that contribute to the emergence of regulatory voids. The diffusion stage is crucial, as it marks the point where technologies have been developed but remain unimplemented; hindering contribution to the transition. The hydrogen transition is characterised by its complexity and fragmented market mechanisms. The absence of clear implementation pathways slows technology adoption, creating a gap between technological readiness and practical application: the essence of regulatory voids in the diffusion stage. When technologies lack proper implementation opportunities, clear conditions, and alignment with the industry processes, they can hardly be integrated into the current market; slowing down the speed of the transition. Enabling scale-up to allow a continuous development loop will accelerate transition progress and can break this pattern.

A wide spectrum of regulations is developed from distinct levels of governance to address regulatory voids, however, in the hydrogen transition this has led to ambiguity and uncertainty among industry parties. These fragmented measures become overly complex, causing confusion and reducing the obtained effectiveness. Thereby, resources are not always adequately allocated across the supply chain to create markets: disallowing to make investment decisions. In the process of creating supporting incentives for the transition, the institutional theory underscores the need for setting industry norms and standards. From the start of the transition, regulators (often governments) must provide clear conditions to set these market standards and allow industries to make investments to bridge supply and demand.
The hydrogen transition reveals that current regulations and subsidies react to explicit market failures. Thereby, companies are opportunistic and only take projects that have an immediate business case, leading to a lack of consistency and fragmentation. This effect must already be actively addressed in the process of the creation of frameworks and setting the complying norms/standards. Resulting in clearer and more comprehensible regulations and subsidies for the industry parties and so will address regulatory voids.

The institutional theory accurately supports the creation of public-private partnerships to incentivise market scalability and overcome regulatory voids in the diffusion stage. Demonstrated by the development of tailored agreements (maatwerkafspraken), that offer industries and governments an understanding of each other's issues at hand by obtaining a collaborative environment. Thereby allowing regulators to set the right conditions for the industries to create scale-up potential. Issues like accurate resource allocation across the supply chain will likewise be addressed in this way. In addition, the infrastructure development void (DRC) can be more effectively mitigated by removing risks related to investment decisions. Offering the opportunity to create adaptive measures to collectively navigate towards suitable solutions that create a solid business case. Creating long-term development of EU standards through public-private partnerships is essential for achieving unity in cross-border hydrogen distribution. By establishing these standards collaboratively, countries can facilitate smoother future developments.

Last, highlighted by the institutional theory, building trust and legitimacy from the start and sustaining this over the transition time is critical for the broader transition process. Institutions that establish a trustworthy and legitimate environment will encourage stakeholders to align with shared objectives and mitigate perceived risks, thereby facilitating earlier investment decisions and enabling progress. Furthermore, institutionalising trust within industries not only supports the current transition but creates a foundation for future transitions, creating a culture of cooperation, stability, and shared advancement that aligns with institutional norms and expectations.

In conclusion, a mission-driven approach towards collaborative regulation and resource allocation, focusing on clear goals, legitimacy, and trustworthiness, will improve the effectiveness of addressing regulatory voids. By aligning supporting market mechanisms with the needs of the transition, stakeholders are incentivised to adopt developed technologies from the diffusion stage, preventing the development speed from slowing down and addressing the emergence of regulatory voids effectively.

9
Practical Recommendations and Considerations

9.1. Practical recommendations

Concerning the overall outcome of this research, several practical recommendations can be made. Especially regarding preventing regulatory voids from emerging or addressing existing regulatory voids.

It is essential, particularly from the perspective of higher levels of government, to maintain as much control as possible over the transition process. This does not mean exerting direct intervention but rather ensuring that transitions are guided by a clear vision and supportive structures: the creation of the conditions. Governments should not merely react to failures but proactively shape the transition by setting strategic goals, creating regulatory certainty, and encouraging industry alignment with consistent principles. The early development of clear standards and guidelines across multiple levels is strongly recommended. The establishment of European standards is often a lengthy process, delaying their effective implementation in member states such as the Netherlands. Furthermore, transnational standards for infrastructure would provide much-needed guidance across multiple countries, accelerating the pace of transition and technology adoption.
Delays in transition projects, as observed with the DRC in the hydrogen sector, require an active and structured response. It is crucial to develop contingency plans in collaboration with both producing and consuming industries (both ends of the supply chain) to prevent stagnation. Without viable implementation opportunities, technologies risk becoming hindered, leading to demotivation in further development, increased stakeholder reluctance, and overall procrastination. Proactive engagement with industry stakeholders is therefore necessary to maintain momentum and ensure continued progress.
To support effective market development, resources (e.g.: standards, regulations, norms, subsidies) must be allocated strategically across the entire supply chain. Current incentives are heavily focused towards the front end, leaving consuming industries (back end) underdeveloped and creating an imbalance that hinders full market integration. A more balanced distribution of incentives would enable consuming sectors to play an active role in the transition. At times, additional guidance may be required to facilitate the progression from technological diffusion to full market adoption, ensuring long-term viability.
Effectively addressing regulatory voids requires a comprehensive understanding of their origins and underlying causes before action is taken. Regulatory gaps often emerge due to unclear market conditions or fragmented governance structures. To bridge these gaps, it is essential to engage relevant stakeholders across the value chain and gain full market insights. A well-informed approach will enable regulators to create targeted and effective frameworks that encourage market development without unintended barriers.
Finally, trust is a critical factor in the success of transition management. A lack of trust, whether due to past policy inconsistencies, abrupt regulatory changes, or failed initiatives, undermines collaboration and slows technology development and adoption within transitions. At the same time, consuming industries often adopt a passive stance, either delaying commitments or considering relocation to more favourable regulatory environments. This results in friction and further erodes confidence between industry and government. Strengthening public-private partnerships through tailored agreements

(maatwerkafspraken) and structured collaboration is essential to restoring trust, aligning objectives, and ensuring that all stakeholders actively participate and so contribute to the transition process.

9.2. Considerations

When analysing the results in Atlas.ti and developing the pattern findings alongside the in-depth findings, several noteworthy considerations emerged that are found interesting to present.

- **Where should governmental support stop?**
  A first consideration that should be explained, is the moment when governmental support in the form of subsidies should be considered enough and should stop. As is reflected in the findings, the attitude towards the creation of the hydrogen market can be marked as quite passive, especially from consumers' perspective. The underlying aspect of the 'wait-and-see' mentality is the creation of a sound business case for the consuming market players. When heavily subsidising this, there will of course be a sound investment decision taken at some point. The passive attitude from the consumers could result in subsidies that are never enough, ultimately leading to a business case that is never 'good enough'. As additionally highlighted in the interviews, considering that companies have settled in Europe due to (foremost) favourable market conditions, the attitude from these can therefore be considered as not completely fair. This should be taken into consideration when supporting the hydrogen market.
- **Market creation and scaling-up: governmental differences**
  A second consideration that emerged during the interviews and the study in general concerns the extent to which governments should intervene in the hydrogen market. Interviewees highlighted that in China, the government plays a decisive role in market creation by mandating production or guaranteeing demand, enabling rapid scale-up. This approach ensures the emergence of a hydrogen market but does so through direct intervention rather than organic industry development.
  In contrast, Dutch regulators do not have the ability to scale up the hydrogen market themselves; rather, their role is to create the regulatory conditions that allow the market to develop independently. The Dutch (also referred to as Western world) approach relies on setting clear rules, standards, and incentives that provide certainty for private-sector investment. While financial instruments such as subsidies can help lower initial barriers, they are economic incentives rather than direct mechanisms for market creation and scaling-up. Ultimately, the responsibility for scaling up lies with industry players, who must respond to these regulatory conditions by investing in infrastructure, technology, and production capacity.
  This distinction between China's state-driven model and the Netherlands' regulatory approach highlights the key challenge of addressing regulatory voids. When regulatory frameworks are unclear or incomplete, market actors face uncertainty, which can hinder investment and delay the transition. Therefore, instead of attempting to scale up hydrogen adoption directly, Dutch regulators must focus on eliminating regulatory uncertainties, ensuring a predictable investment climate, and enabling the private sector to drive market growth.
- **The effect of void specific measurements?**
  Addressing regulatory voids can be approached either through targeted, void-specific measures or a broader, collective strategy. Void-specific approaches offer faster and more focused solutions but risk fragmentation and inconsistencies. Collective strategies are slower but promote comprehensive and sustainable outcomes by aligning stakeholders and addressing systemic challenges. A hybrid approach, combining immediate interventions for urgent voids with long-term collective efforts, may provide an efficient approach as well. The choice between these methods should consider the urgency, maturity of the transition, and the need for ongoing evaluation to adapt regulatory frameworks and subsidy schemes effectively.

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A
Data Management and Plan

This part of the appendix highlights the Data Management Plan (DMP) (Section: A.1) and the consent form (Section: A.2) used before starting the interviews.

A.1. Data Management Plan

The complete Data Management Plan can be found on the following pages and has been reviewed by Lora Armstrong from Delft University of Technology.

Plan Overview

A Data Management Plan created using DMPonline

Title: Accelerating the Development of Hydrogen Infrastructure

Creator: Jasper Smit

Affiliation: Delft University of Technology

Template: TU Delft Data Management Plan template (2021)

Project abstract:

The objective of this research is to analyse the current legislation and regulations relating to pipeline construction for a hydrogen network. In order to gain an understanding of the current status of development, information will be obtained from governmental institutions. In addition, the research will investigate the bottlenecks for the construction of pipelines based on information derived from lighthouse projects, theoretical knowledge and earlier feasibility studies. The aim of this research is to identify the gaps between the technical innovations and the current status of technical developments.

The project known as Hy3 (https://hy3.eu/) provides the foundation for this study. The final desired outcome is to develop a regulatory framework that will facilitate the implementation of a hydrogen network. This framework will include a series of "building blocks" designed to identify the key steps that must be taken from a government and policy perspective to accelerate the implementation process.

ID: 153520

Start date: 09-07-2024

End date: 31-01-2025

Last modified: 30-09-2024

Accelerating the Development of Hydrogen Infrastructure

0. Administrative questions

Committee/supervisors:

- Chair: Martijn Leijten
- 1st supervisor: Shubham Sharma
- 2nd supervisor: Daan Schraven
- Company supervisor: Moreno de Respinis

Support staff contact meeting: Lora Armstrong

I. Data description and collection or re-use of existing data

Type of data	File format(s)	How will data be collected (for re-used data: source and terms of use)?	Purpose of processing	Storage location	Who will have access to the data
Citations	.pdf	Publicly available literature	Compare insights + analyse processes	TU Delft OneDrive	Personal use (Jasper Smit), my supervisors from the TU Delft and Arcadis (committee)
Additional relevant literature	.pdf	Publicly available literature	Analyse processes from governments and technical developments	TU Delft OneDrive	Personal use (Jasper Smit), my supervisors from the TU Delft and Arcadis (committee)
Voice recordings of Observations	.mp3 (or other relavant audio file type)	Interview	Use to transcribe interviews	TU Delft OneDrive	Personal use (Jasper Smit)
Observational notes from project meetings. No personal information will be written down.	.pdf	Restricted meetings with involved people in the Hy3-project	Analyse processes from governments and technical developments	TU Delft OneDrive	Personal use (Jasper Smit), my supervisors from the TU Delft and Arcadis (committee)(Anonymised quotes can potentially be published in the thesis).
Informed consent form for interviews	.pdf	Interview	Request permission for data	TU Delft OneDrive	Personal use (Jasper Smit)
Contact information interviewees	.pdf	Interview	Analyse processes from governments and technical developments	TU Delft OneDrive	Personal use (Jasper Smit)
Voice recordings of interviews (if meeting is via Teams, an MS Teams transcription will be used)	.mp3 (or other relevant audio file type)	Interview	Use to transcribe interviews	TU Delft OneDrive	Personal use (Jasper Smit)
Interview transcripts	.pdf	Interview	Analyse processes from governments and technical developments	TU Delft OneDrive	Personal use (Jasper Smit), interviewed participants
Anonymised interview transcripts	.pdf	Interview	Analyse processes from governments and technical developments	TU Delft OneDrive	Personal use (Jasper Smit), my supervisors from the TU Delft and Arcadis (committee)(Anonymised quotes can potentially be publisched in the thesis).
Analysed data supporting results of thesis	.pdf	Qualitative analysis	Analyse the effect of the new identified process and building blocks.	TU Delft OneDrive	Personal use (Jasper Smit), my supervisors from the TU Delft and Arcadis (committee)(Anonymised quotes can potentially be publisched in the thesis).

- < 250 GB

II. Documentation and data quality

- Methodology of data collection
- README file or other documentation explaining how data is organised

III. Storage and backup during research process

- OneDrive

IV. Legal and ethical requirements, codes of conduct

- Yes

Interviews and involved people in the project that cannot be shared publically.

- Yes

I will conduct interviews and experiences/insights of the interviewees will be noted.

- Yes, confidential data received from commercial, or other external partners

I will work with data that is gathered already in the project and that cannot be shared before they (they = Arcadis) publisch it.

As a master's student, I am not required to publish the underlying data sets. The underlying data will be shared in the appendix of the thesis report (where that is possible). As a principle researcher, I will oversee the access of the data from the project until the publication of the thesis report. If data is not accessible to everyone, it will be made unavailable. The supervisors will all have access to the data that I use for my thesis. Only data dat is de-identified will be shared.

- Photographs, video materials, performance appraisals or student results
- Other types of personal data - please explain below
- Data collected in Informed Consent form (names and email addresses)
- Email addresses and/or other addresses for digital communication
- Signed consent forms
- Names and addresses

Information on working status and background/experience. Like

Professionals and participants who will be interviewed, an overview of the data subjects is given below:

- Project managers
- Involved experts
- Policy makers
- Representatives from public/governments
- Process managers.

- No

- Informed consent

Prior to the commencement of the interview, the researcher must obtain permission (informed consent) to record the interview. Each interview will be transcribed as soon as possible. Once the transcription has been agreed upon, the recording will be deleted. The transcript of the interview is then checked with the respondent. The transcript is sent to the respondent, who is then given the opportunity to provide comments on the written text. This process allows the respondent to check whether the transcript is a correct representation of the interview or if it contains any inaccuracies or unwanted sensitive statements.
Prior to the interview, the respondent will be asked to provide informed consent. Only upon receipt of this consent will the interview proceed. I will request the email address of the respondent so that I can email the anonymised quotes of the respondent that I intend to use. I will only use these anonymised quotes if the respondent agrees to their use.

- Same storage solutions as explained in question 6

- None of the above applies

- Anonymised or aggregated data will be shared with others
- Personal research data will be destroyed after the end of the research project

- 10 years or more, in accordance with the TU Delft Research Data Framework Policy

- For research purposes, which are in-line with the original research purpose for which data have been collected

- Yes, in consent form - please explain below what you will do with data from participants who did not consent to data sharing

I will ask if they can be de-identified directly. Otherwise, I will not be able to use this source and look for another source.

V. Data sharing and long-term preservation

- No other data can be publicly shared - please explain below why data cannot be publicly shared

I will only share the anonymised interview transcripts in the appendix of the thesis report. The analysed data will be shared in the appendix as well.

- My data will be shared in a different way - please explain below

My data will be shared in the appendix of the thesis.

- < 100 GB

- As soon as corresponding results (papers, theses, reports) are published

- Other - Please explain

Not applicable.

VI. Data management responsibilities and resources

- Yes, leading the collaboration - please provide details of the type of collaboration and the involved parties below

The thesis is written in colaboration with Arcadis. The supervisors will have acces to my data during the research as specified in Q3.

Dr. M (Martijn) Leijten, assistant professor at the TU Delft.
Email adres + phone number:

-
-

Not applicable.

A.2. Consent interviews

The following pages contain the email and consent form sent to potential participants. At a later stage, once the interview is scheduled, the interview protocol is provided to inform the interviewee about the type of questions and aid in their preparation. The interview protocol can be found in Appendix B.

Beste lezer,

U bent uitgenodigd om onderdeel te zijn van een onderzoek genaamd 'Accelerating the Development of hydrogen infrastructure'. Dit onderzoek wordt uitgevoerd door Jasper Smit van de Technische Universiteit Delft, in samenwerking met Arcadis.

Het doel van dit onderzoek is het versnellen van de energie transitie op het gebeid van waterstof infrastructuur ontwikkeling door proces stappen te identificeren gerelateerd aan transitie theorieën. Het interview zal tussen de 30-60 minuten in beslag nemen. De data verzamelen met dit onderzoek zal worden gebruikt voor een kwalitatieve analyse voor mijn onderzoek. U wordt dus gevraagd om deel te nemen aan het interview en daarmee dus bij te dragen aan het (onafhankelijke) onderzoek.
De data die verzamelt zal worden met onder andere dit interview zal alleen gebruikt worden voor dit onderzoek. Daarbij is het mogelijk om op verzoek gegeven data te anonimiseren. We zullen risico's minimaliseren door geen persoonlijke gegevens te documenteren. Alle verzamelde data zal worden opgeslagen op de door de TU Delft aangedragen OneDrive en zal na verwerking worden verwijderd.

Uw deelname aan mijn onderzoek is volledig vrijwillig. Terugtrekken zonder reden is op elk moment mogelijk en u bent ook vrij om antwoorden op vragen niet te geven. Na elk interview zal een samenvatting worden gestuurd ter validatie.

Naam onderzoeker:	Jasper Smit
Mail onderzoeker:	j.r.smit@stduent.tudelft.nl
Telefoonnummer onderzoeker:	+31(0)637409818

Dear reader,

You are invited to take part in a study called 'Accelerating the development of hydrogen infrastructure'. This research is being conducted by Jasper Smit of Delft University of Technology in collaboration with Arcadis.

The aim of this research is to accelerate the energy transition in the field of hydrogen infrastructure development by identifying process steps related to transition theories. The interview will take 30-60 minutes. The data collected from this research will be used for qualitative analysis for my research. Therefore, you are asked to participate in the interview and thus contribute to the (independent) research.

The data collected through this interview will only be used for this research. If you wish, it is possible to anonymise the data provided. We will minimise risks by not documenting any personal data. All collected data will be stored on the OneDrive provided by TU Delft and will be deleted after processing.

Your participation in my research is completely voluntary. You can withdraw at any time without giving any reason and you are also free not to answer any questions. After each interview, a subtract will be made and shared to validate.

Name of the researcher:	Jasper Smit
Researcher email:	j.r.smit@stduent.tudelft.nl
Researcher's telephone number:	+31(0)637409818

Consent form interview (please thick the boxes on the right)	Yes	No
A) General consent: goal of the research, tasks of the participants and participation on voluntary basis		
1. II have read and understood the information about the research dated ..../..../....., or it has been read to me. I have had the opportunity to ask questions about the research and my questions have been answered to my satisfaction.	☐	☐
2. I am volunteering for this study and I understand that I can refuse to answer any questions and withdraw from the study at any time without giving a reason.	☐	☐
3. I understand why this research is conducted and that it includes the following: • The orientation of the research is to analyse how via the identification of process steps for regulatory framework construction, the speed of implementation can potentially be improved; • Interviews will be recorded via phone, Teams or notes will be taken and the recordings will be saved at the TU Delft OneDrive; • The recorded interviews will be transcribed and if needed anonymised, at the end of the research the data will be deleted.	☐	☐
4. To goal of this study is to be finished before the 1st of March 2025 and data (or anonymised data) can be published by then.	☐	☐
B) Potential risks for participant (data protection)		
1. I understand that participating in this research could have the following risks: data leak and loss of recorded files/transcripts. I understand that these risks are minimized by using TU Delft official OneDrive and deleting the processed files immediately.	☐	☐
2. I understand that my participation can result in personal identifiable data, with potential risk that I can be identified.	☐	☐
3. I understand that under the General Data Protection Regulation (GDPR) some of this personally identifiable research data is considered sensitive.	☐	☐
4. I understand that the following steps will be taken to prevent any data leak or other inconvenience related to data will be taken to protect my privacy: • Data will only be stored at the TU Delft OneDrive; • Data will be transcribed and if needed anonymised, research involved staff from the TU Delft and Arcadis do only have permission to see the anonymised data; • After transcription the records will be deleted.	☐	☐
5. All data will be deleted after the 1st of March 2025.	☐	☐
C) Publication and application/relevance of research		
1. I understand that after the research, the (anonymised) information will be used to analyse the impact of environmental law on public participation. This analysis may be published in the Master's thesis and academic reports.	☐	☐
2. I give permission to quote my answers, ideas or other contributions anonymously in resulting products.	☐	☐
D) Data storage and access		
1. I give permission for the anonymised data collected about me (processed transcripts) to be used in this research, which will then be published in the TU Delft repository.	☐	☐

Name participant: Signature participant: Date:

____________________ ____________________ _______

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B
Interview Protocol

The following pages present the interview protocol used during the interview sessions. While the core structure of the protocol remained consistent across all interviewees, slight modifications were made depending on the stakeholder type. Since six relevant stakeholder groups were identified, questions related to regulatory voids were tailored to gather more specific insights based on each stakeholder's background and interests.

Interview protocol

The main aim of the interview is to be open and let the interviewee talk about how they want to fill in or how they see the future of the hydrogen infrastructure. The questions below are suggestions that can be used during the interview. Of course, the order of the questions and the exact questions will be decided during the interview itself.

Start and introduction:
Thank you very much for agreeing to be an interviewee. I am conducting interviews with different groups of stakeholders to gain an in-depth understanding of the development of the hydrogen infrastructure, which is why I am interviewing you. There is no wrong answer in this interview as I am interested in your opinion and experience of the energy transition that is taking place.

Before we begin the interview, I would like to discuss the consent form I sent to you via email. Did you have a chance to read it, and do you have any comments or changes you'd like to make? To formalize the agreement now, I have started the recording, as this part of the process needs to be documented. I will guide you through the consent form, and please feel free to highlight any specific points. I addition to double check the usage, a draft of this report will be sent to you around mid-January so you can review it for any potential misunderstandings or changes you'd like to make. If everything is clear, we can proceed with the interview.

Introduction to research:
The objective of my research is to identify concrete steps that can be taken to accelerate the development of the hydrogen infrastructure. As we all want to move to a new energy system that is more sustainable, hydrogen as an energy carrier can be a good solution. While progress has been made over the past decade, the pace of implementation seems to have stagnated.
To overcome this stagnation, I look at the relationship between regulatory development and technological innovation. As the literature outlines, the implementation of the hydrogen infrastructure is stagnating. This is since technological innovations are not adequately regulated, also known as a regulatory void. Regulatory frameworks in place may hinder the development due to mis regulating the development of not existing at all. With this interview, I hope to gain more insight and discover how regulatory development can help prevent hydrogen adoption from slowing down.

Personal background introduction:
Before we are starting the interview, check if the consent form is clear and if the interviewee understands the goal of this interview. In addition, let the interviewee give an introduction.

Introduction related to actor:
Here the interviewee will relate to their company background, what market they are in and how to involve (or not) hydrogen in their future system. This can be different points of view: as in production of hydrogen, providing of the network, consuming hydrogen, an academic expert, or a government that tries to stimulate the hydrogen implementation.

- What type of playing field are you in?
- From what actors/stakeholders are you dependent?
- How do you feel about the current developments?

General hydrogen transition and relation to regulatory development
From literature point of view and reading hydrogen publications, there are a lot of parties that ask for clear regulations regarding the implementation of hydrogen. In addition, the pressure from society to move towards a more sustainable energy transition becomes bigger. The goal of this research is to find out what can be done to accelerate the energy transition, specifically the implementation of hydrogen.

- What is your general idea of the implementation of hydrogen?
- How do you think the implementation of hydrogen is moving forward?
- Where do you see the hydrogen infrastructure development lagging?
- How can regulations help overcome the infrastructure development and give structure to the process?

Relation to bottlenecks:
For my research I have performed a case study that highlighted two bottlenecks regarding the implementation of the hydrogen infrastructure: incompletion of the network, storage and the hydrogen pricing/market model. I want to discuss these bottlenecks separately in relation to regulatory steering.

Questions for stakeholder group: experts:
Regulatory void: Incompletion of the network: DRC delay:

- Where do you think the bottlenecks for the DRC delay are?
- How do you see these bottlenecks being solved (regarding facilitating the implementation speed)?
- What personal observations can you share about the implications of the delays for the region and its future development?
- Scenario:
  - As quick as possible:
    - How can the DRC implementation being accelerated and what is your position or task in order to make this happen?
  - Delayed:
    - How will you act when the DRC will be delayed (confirmed delay 2030) and how would this influence the implementation speed of the hydrogen network?
- Have you encountered any specific regulatory roadblocks that have impeded the smooth advancement of the DRC?
- From your point of view, how do you believe that existing or future regulations can influence the delay of the DRC?
- Considering policy development and technology development, what side is hindering the process?
- What stakeholder is at this moment hindering the development?
- How can this stakeholder help the hydrogen implementation help to accelerate?
- What type of regulatory steering is needed in order facilitate the acceleration?

Regulatory void: Hydrogen market development:

- How do you perceive the current challenges surrounding hydrogen market development?
- What factors play a primary role from the perspective of final investment decisions (FID)
- in accelerating the hydrogen implementation from your companies' perspective?
- What do you see as obstacles that hinder the effective development of a hydrogen
- market?

- What is necessary from your perspective to bring the hydrogen market in place?
    - Which stakeholders are crucial?
    - In which way could a market sustain itself from both private and public
- stands (goal: public support needed, subsidy)?
- What regulatory measures do you think are necessary to spur the growth of the hydrogen
- market?
- How / what are elements that are interesting to take from (for example the gas market)
- that need to be implemented in the hydrogen market?
- What stakeholder is at this moment hindering the development?
- How can this stakeholder help the hydrogen implementation help to accelerate?
- What type of regulatory steering is needed in order facilitate the acceleration?

Questions for stakeholder group: hydrogen importer:
<u>Regulatory Void: DRC Delay:</u>

- Where do you think the bottlenecks for the DRC delay are from the perspective of import logistics and infrastructure readiness?
- How would you prioritise actions to facilitate faster DRC implementation, considering import demands?
- How have delays in the DRC affected your import operations and long-term strategic planning?
- Scenario:
    - As quick as possible:
        - What role could importers play in accelerating DRC implementation, and how do you envision contributing to this?
    - Delayed:
        - How would a confirmed DRC delay to 2030 impact your import operations, and what mitigation strategies would you employ?
- Have import-specific regulatory barriers impeded progress on the DRC?
- How could future regulations directly affecting import logistics help address the delay?
- From your perspective, are delays more influenced by technology, infrastructure, or regulatory issues?
- Which stakeholder, in your view, has the most influence over resolving the delay, and how could they help?

<u>Regulatory Void: Hydrogen Market Development</u>

- How does the current lack of a developed hydrogen market affect your ability to scale imports?
- What primary factors would influence your decision to invest in hydrogen import infrastructure?
- What do you identify as critical obstacles for establishing a viable hydrogen import market?
- From your perspective, what is required to create a sustainable market for hydrogen imports?
    - Which stakeholders must align to make this happen?
    - What level of public-private cooperation or subsidy is needed to support importers?
- What lessons can the hydrogen market adopt from existing gas import frameworks?
- How can other stakeholders support importers in accelerating market readiness?
- What regulatory steering mechanisms do you think would facilitate the growth of hydrogen imports?

Questions for stakeholder group: hydrogen consumer:

Regulatory Void: DRC Delay

- How do DRC delays influence your ability to access affordable and reliable hydrogen?
- What solutions or interim measures would you suggest to minimise the impact of DRC delays on consumers?
- How have delays in the DRC affected your planning for hydrogen integration into your operations?
- Scenario:
  - As quick as possible:
    - What support or commitments could consumers offer to accelerate DRC implementation?
  - Delayed:
    - If delays extend to 2030, how would this affect your operational efficiency and decarbonisation goals?
- Have you faced specific consumer-side regulatory barriers that hinder hydrogen adoption?
- How do you think existing or potential regulations could better facilitate consumer access to hydrogen?
- From your perspective, which stakeholders are creating bottlenecks, and how could they address consumer needs better?

Regulatory Void: Hydrogen Market Development

- What challenges do you currently face in sourcing hydrogen at a competitive price?
- What factors would motivate you to make final investment decisions in hydrogen-powered solutions?
- What obstacles hinder your ability to adopt hydrogen technologies effectively?
- What do you think is necessary to ensure a reliable and affordable hydrogen supply for consumers?
  - Which stakeholders should lead these efforts?
  - What level of public support or subsidy is crucial to encourage consumer uptake?
- What features from other markets (e.g., natural gas) could make hydrogen more appealing to consumers?
- How could regulations help incentivise consumer adoption of hydrogen?

Questions for stakeholder group: (semi-)governments:

Regulatory Void: DRC Delay

- Where do you see the bottlenecks in achieving DRC implementation from a governance perspective?
- What policy tools or resources could governments use to accelerate DRC development?
- How do DRC delays influence broader energy transition policies in your jurisdiction?
- Scenario:
  - As quick as possible:
    - What measures could government bodies adopt to streamline DRC implementation?
  - Delayed:
    - If delays extend to 2030, how would this influence regional and national energy strategies?
- Are current regulations sufficient to manage the DRC rollout, or do they require revision?

- How can governments balance regulatory oversight with accelerating development?
- Which stakeholder do you believe holds the key to resolving the DRC delay?

Regulatory Void: Hydrogen Market Development

- What are the biggest challenges in shaping a national or regional hydrogen market?
- What regulatory frameworks are needed to attract public and private investments in hydrogen?
- How can government incentives support market development?
- What role should government collaboration with private stakeholders play in building a hydrogen market?
- How can lessons from existing energy markets (e.g., natural gas) inform hydrogen market policies?
- Which stakeholder relationships require improvement to accelerate hydrogen adoption?

Questions for stakeholder group: hydrogen industry provider:
Regulatory Void: DRC Delay

- How do DRC delays impact your ability to supply critical hydrogen technologies or infrastructure?
- What technological or logistical solutions could help speed up DRC implementation?
- What role do you see for industry providers in mitigating the effects of DRC delays?
- Scenario:
  - As quick as possible:
    - How could your industry accelerate DRC development through innovation or partnerships?
  - Delayed:
    - If delays extend to 2030, how would this impact your business model or product delivery timelines?
- Are there specific regulatory gaps that hinder your ability to contribute to DRC progress?
- How can regulatory changes better support the industry's role in hydrogen infrastructure development?

Regulatory Void: Hydrogen Market Development

- What are the biggest challenges in providing hydrogen infrastructure or services to a nascent market?
- How do market uncertainties affect your decisions to invest in or scale up operations?
- What obstacles are preventing efficient collaboration between providers and other stakeholders?
- What regulatory measures would enhance market stability for industry providers?
- How can industry stakeholders contribute to establishing a sustainable hydrogen market?

Questions for stakeholder group: hydrogen producer:
Regulatory Void: DRC Delay

- How do DRC delays influence your production timelines and delivery capabilities?
- What role do producers play in overcoming delays and ensuring network readiness?
- How have delays affected your investment in hydrogen production facilities?
- Scenario:
  - As quick as possible:
    - How could producers contribute to accelerating DRC implementation?
  - Delayed:

    - If delays extend to 2030, what adaptive strategies would you employ?
- What producer-specific regulatory barriers are hindering the hydrogen network's development?
- How could regulations better support producers in achieving DRC milestones?

Regulatory Void: Hydrogen Market Development

- What challenges do you face in producing hydrogen at scale while ensuring profitability?
- How does the lack of a developed market affect your investment decisions?
- What factors would motivate you to increase production capacity?
- What regulatory measures are necessary to stabilise demand and market pricing for hydrogen?
- How can hydrogen producers collaborate with other stakeholders to create a sustainable market?

Situational sketch for 2035:
The situation is the following, when fast forwarding to 2035, there is a lot more determined in terms of energy transition. Different infrastructure will be there and what is currently unthinkable, might by than be common practice. In terms of regulations, there has been a big switch as well. Let's reflect a bit on how we got here.

General:

- What do you consider the energy configuration to be by 2035?
- What were the most critical factors that shaped this?

More specific hydrogen:

- So, the hydrogen configuration is ??% in the 2035 configuration, what was the biggest struggle/hurdle for hydrogen to come into play?
- How were bottlenecks like storage capacity or infrastructure addressed over these two decades?
- What were key regulatory decisions influencing the pace of the hydrogen network development?

Follow-up scenario probing questions:

- For example, mentioning the rapid expansion of infrastructure: was this mainly driven by technology development or regulatory interventions?
- Were there any specific regulatory voids that persisted for too long, and how were these finally addressed?
- Looking back, what would you say were the most unexpected developments in the hydrogen network by 2035?
- Wat do you consider the energy configuration to be by 2035?
- What were the most critical factors that shaped this?

More specific hydrogen:

- So the hydrogen configuration is ??% in the 2035 configuration, what was the biggest struggle/hurdle for hydrogen to come into play?
- How were bottlenecks like storage capacity or infrastructure addressed over these two decades?
- What were key regulatory decisions influencing the pace of the hydrogen network development?

Follow-up scenario probing questions:

- For example, mentioning the rapid expansion of infrastructure: was this mainly driven by technology development or regulatory interventions?
- Were there any specific regulatory voids that persisted for too long, and how were these finally addressed?
- Looking back, what would you say were the most unexpected developments in the hydrogen network by 2035?

Closing:
Thank you for having you as an interviewee. It was an interesting conversation with new and important highlights for my investigation. Thereby I want to ask you if you have anything last to say related to the questions or any other business?

C
Partners Hy3$^+$ Project

Figure C.1 presents the partners involved in the project. These partners are part of the study board and play a role in influencing decisions made throughout the study process.

Figure C.1: Partners involved in the Hy3$^+$ project (HY3+, 2024).

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D
Overview Cumulative Findings

This appendix presents the results of the analysis from the interviews, see Figure 5.1 and Table 3.2, that were conducted. For this analysis, the Gioia method is used as explained in Chapter 3: Research Methodology. The interview transcripts were analysed and coded with first order codes based on their meaning (subject, implication, et cetera). These responses were thereafter mapped towards second order terms (also referred to as themes) to gain a more thorough understanding and to identify patterns. The mapping of the first order terms into the second order terms to find the patterns can be seen in Table D.1.

Table D.1: Overview of first order terms belonging to second order terms.

Second order terms:	**First order terms:**
Cooperation and Stakeholder Integration	Connection between stakeholders, Cooperation, Dependency, Different stakeholder interests, Gasunie (semi-Government), Government, Industry (supply chain), Local industries (location specific), Private Parties, Public parties/institutions, Society
Economic Incentives and Market Stimulation	ETS price, High consumer prices, General cost related, High electricity price, Hydrogen Bank development, Investments, Level playing field, Cost of production/operations, Postpone investments, Subsidy/funding
External Pressures and Policy Drivers	China developments, EU pressure, Pressure, External developments
Infrastructure and Technology Development	Development development, Network construction, Point to point, Hydrogen purity, Space availability, Storage options, Transportation issues
Knowledge Development and Capacity Building	Early stages of development, Efficiency, First-movers advantage, Guidance, Hydrogen education, Moving industries, Principle agent problem, Production of hydrogen, Risks
Long-term Vision and Strategic Goals	2035 vision, Commitment, Achievable goals, Long-term goals, Speed of development, Stimulating
Market and Institutional Adaptation	Alternatives, Ammonia, Consumer, FID, Gas market, Import of hydrogen, Integration, interim solution, LNG comparison, Monopoly structure, National differences, Redundant, Supply chain
Regulatory Guidance and Standardisation	Blue Hydrogen, Electrolysers, Green Hydrogen, Norms, Permit, Regulation, Safety, Security, Standardisation, Transnational
Trust and Transparency Creation	Complex, End users, Responsibility, Sensitive, Transparency creation, Trust, Wrong people in place

The following three sections will present the distribution of responses to the second order themes are three different ways: normal, normalised, and responses that address a specific void.

D.1. Stakeholder response distribution

Figure D.1 illustrates the distribution of the responses over the identified themes. Beneath each representation of the second order theme, the total number of responses is presented to that specific theme.

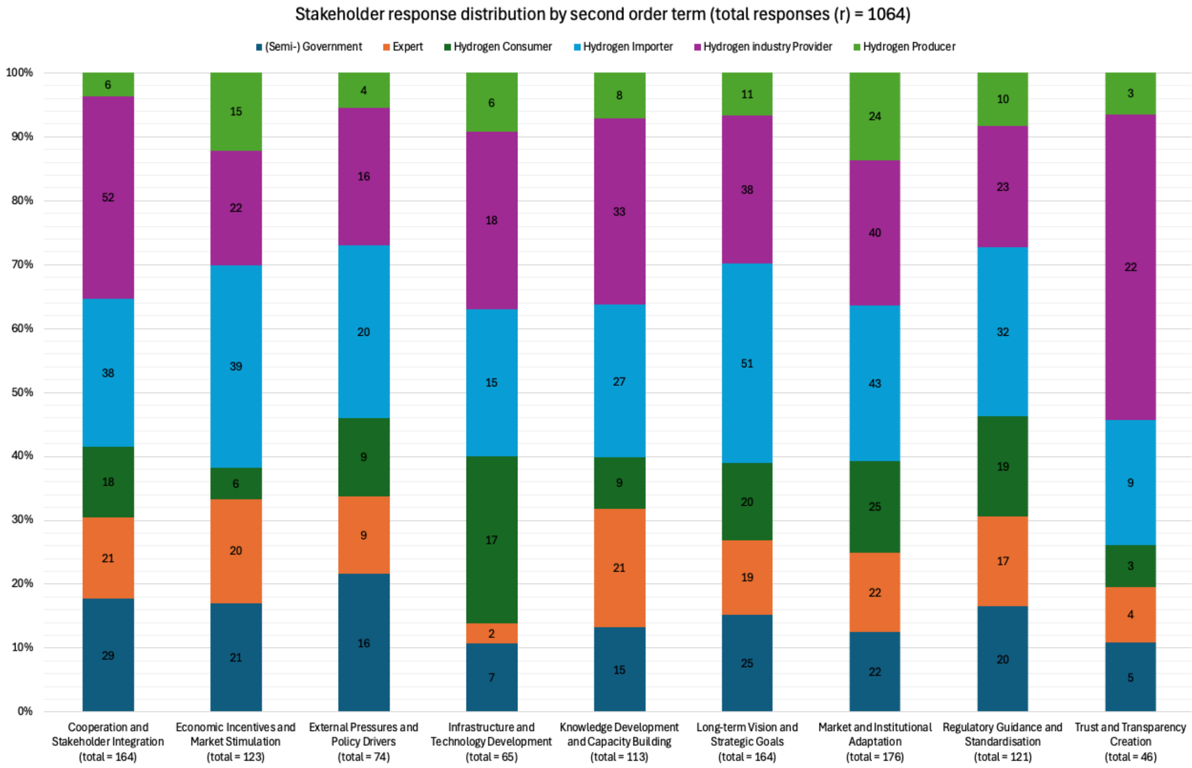

Figure D.1: Primary data analysis from interviews (made by author).

D.2. Stakeholder response distribution normalised

Figure D.1 illustrates the normalised distribution of the responses that can be concerned with one of the identified themes. Beneath each representation of the second order themes, the total number of responses is presented to that specific theme. The table is normalised based on the responses from the stakeholder group with the most responses in total, the Hydrogen industry Provider with 273 responses. This way of normalising the data presents an approach to creating equality between the stakeholders: every stakeholder group has as much response opportunity as the most responding stakeholder group.

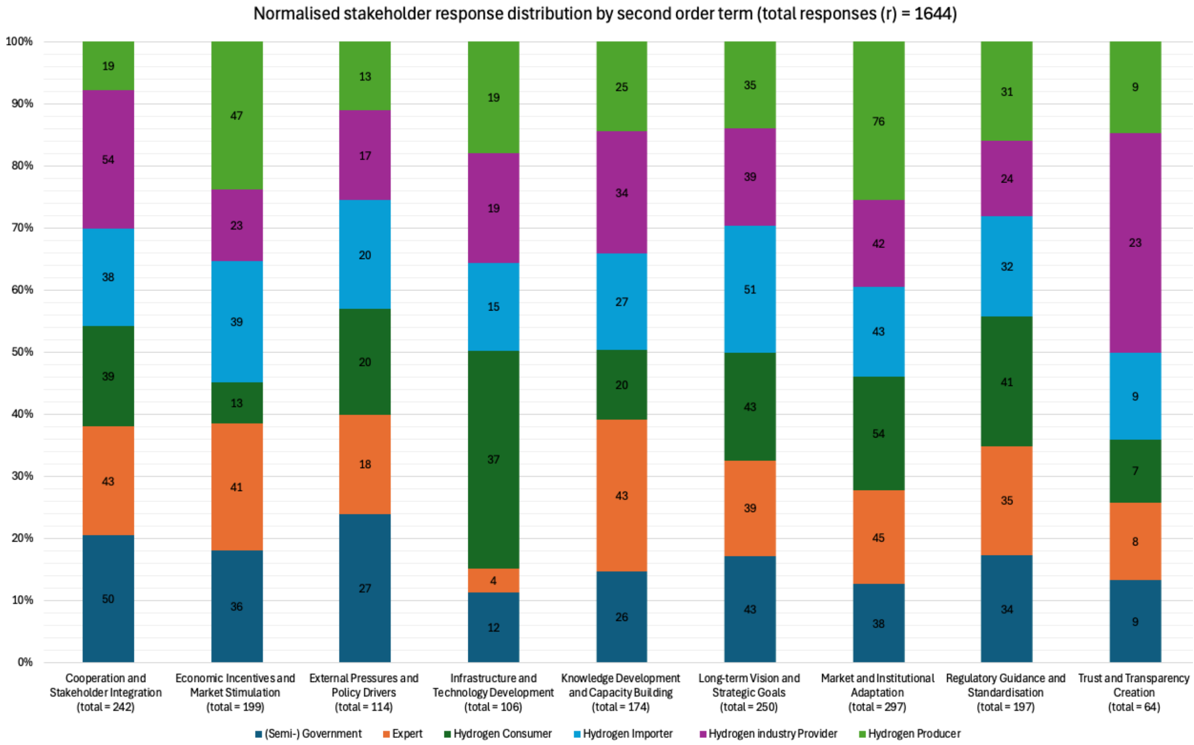

Figure D.2: Primary data analysis from interviews normalised graph (made by author).

D.3. Stakeholder response distribution to regulatory voids

During the interviews, participants were introduced to two regulatory voids identified in the case study:

- Regulatory void related to infrastructure development (ID)
- Regulatory void related to market development (MD)

The responses regarding these regulatory voids were analysed and are visualised in Figure D.3 to identify emerging patterns [1]. The primary objective of this figure is to explore how these voids can be effectively addressed through various methods, as indicated by the interviewees.

Figure D.3 illustrates the responses in a two-step process, with clear connections between elements. The dotted lines represent the number of responses from each stakeholder group that concerns one of the two specified regulatory voids. Straight lines indicate the number of responses linking the voids to the identified second order categories (Table D.1). The thickness of the lines signifies the relative importance of the responses, with thicker lines indicating a higher number of responses or stronger connections between elements.

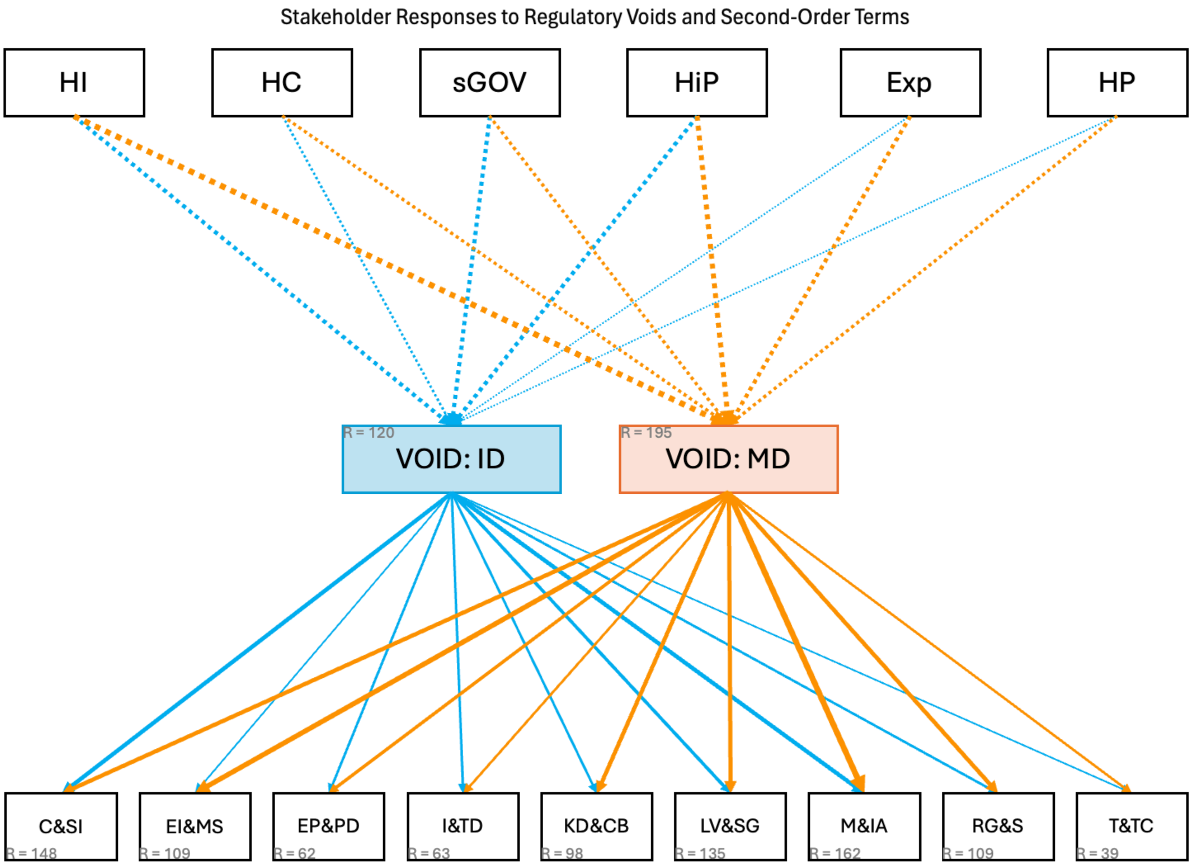

Figure D.3: Stakeholder response analysis related to the regulatory voids (made by author).

[1] Note: There are a total of 120 and 195 responses related to regulatory voids regarding the infrastructure development and market development, respectively. In contrast, the total responses that were related to second order themes amounted to 925. This variance arises because multiple first order terms can be referring to a specific void, and these terms may also relate to multiple second order categories.

D.4. Overview of interview instances

A summary of relevant instances that support Chapter 6: Findings and Chapter 7.1.1: Discussion,is presented in Table: D.2. The first column presents the number of the quote, whereafter it is fully presented. The third column presents the relation to the interviewee and the second order theme is presented in the last column (as in line with the Gioia methodology discussed in Chapter 3 and Table 5.3). An complete map is presented after this table and can be used while reading the findings and discussion.

Table D.2: Summary of insights from interviews conducted (part 1/5).

#	Instance:	Role:	Theme:
#1	Although Rotterdam is a key import hub, it lacks a direct and robust connection to the Rhine-Ruhr area. Without this connection, we risk losing the 'first mover' advantage, a position that Antwerp might successfully secure.	Exp 1	LV&SG
#2	Balancing, certification, pilots, and similar initiatives are currently being developed at the national level. Ideally, these would be scaled up and harmonised at a European level. While there is dialogue between these initiatives, from a market perspective, it would be far more effective if such systems were developed on a broader, Europe-wide scale to ensure compatibility.	HI 4	EP&PD; M&IA
#3	Establishing this public-private partnership is essential, as neither the government nor the private sector can achieve this alone.	HI 1	T&TC
#4	Safety standards must always be applied, but the challenge lies in navigating procedures where certain technical aspects or rules remain undefined. It becomes an enormous puzzle, especially for modalities where regulations are not yet fully established.	sGOV 1	I&TD
#5	The DRC serves as a lifeline, enabling transit to the hinterland (Rhine-Ruhr area) and connecting the various industrial clusters within the Netherlands. The importance of the DRC for national and cross-border connectivity cannot be overstated.	HiP 3	KD&CB
#6	The national government has its own views on what needs to be done, while the European government imposes additional regulations. This creates a landscape of competing interests. We see this reflected in some of our clients, especially those with American parent companies, who focus heavily on economic aspects and ensuring compliance with laws and regulations.	Exp 2	EI&MS; RG&S
#7	The processing side is, of course, a different matter. Pricing factors and uncertainty around demand play a key role there. You could view this as a market-related issue.	Exp 1	EI&MS
#8	Beyond the vital relationship between consumers and governments, it is crucial for the European Union to establish uniform rules and clear legislation for countries like the Netherlands, Belgium, and Germany. A level playing field within the EU would greatly enhance the stability and predictability of investments.	HC 1	C&SI
#9	By appointing a single entity—Gasunie—as the sole developer of the hydrogen network, the government has effectively created a monopoly. This decision, made without sufficient regulatory frameworks, undermines market competition and reduces the principal's ability to influence the agent's actions.	HC 2	C&SI
#10	It was decided that hydrogen, and possibly CO2, would be assigned to Gasunie here. This creates a monopoly, with only one party allowed to manage it. This brought it into a regulated system, which is still being developed. Previously, it operated in an economic model with private companies, who could have implemented it earlier. Naturally, this has led to delays.	HI 2	C&SI
#11	Stakeholders had anticipated the DRC to be operational within a specific timeframe. However, the absence of guarantees regarding its operational date introduces new challenges and undermines trust	HI 2	T&TC
#12	The Ministry of Economic Affairs should focus on determining societal needs and outlining what must be developed to establish a hydrogen economy. However, confusion arises when other stakeholders, like the Ministry of Finance, prioritise financial returns over broader economic goals, such as creating hydrogen-related jobs within the Netherlands.	HC 2	C&SI

Table D.3: Summary of insights from interviews conducted (part 2/5).

#	Instance:	Role:	Theme:
#13	The new hydrogen pipeline is managed by Gasunie, which fully took over after starting as a joint effort. This was a deliberate decision by the KGG to avoid a joint venture. While the market is not yet regulated, it likely will be in the future. For us, the key is simply getting the job done and be able to transport hydrogen.	HI 1	C&SI
#14	The structure of the government hinders progress in the hydrogen transition. KGG (former EZK) aims to promote the hydrogen economy, boost employment, and deliver societal value, while also ensuring a good return on investment. However, Gasunie holds a monopoly over the hydrogen infrastructure, with its own financial priorities. This misalignment of goals creates a principal-agent problem, where societal and industry ambitions risk being overshadowed by the agent's self-interest.	HC 2	LV&SG; EI&MS
#15	Yes, aspects like balancing, certificates, pilots, and similar developments are already being worked on. These efforts are currently being developed at the national level, but ideally, they would be scaled up more broadly. While these initiatives are in conversation with one another, from a market perspective, it seems to us that development at the European scale would be the most beneficial.	HI 4	M&IA
#16	Delays are not unusual in large projects, but they can cause concern among market players and create uncertainty about timelines and locations. For instance, when planning electrolyser projects, questions arise about which parties and locations will be ready for taking them.	sGOV 1	M&IA
#17	Governments need to make strategic decisions without delving too much into detail—like 'levers' they can adjust. Missteps in these adjustments have immediate consequences. Germany is currently demonstrating how to get this right, while the Netherlands is falling behind. As a result, companies are choosing to modernise factories in Germany rather than in Rotterdam. This highlights the importance of governments creating the right conditions to keep investments within their borders.	HI 1	EI&MS; RG&S
#18	I firmly believe that the government has a crucial guiding role to play. If this is left entirely to the market, nothing will happen due to the high levels of uncertainty. Companies will not invest in their own hydrogen infrastructure if they are unsure whether it will ever be utilised. This creates a disadvantage compared to competitors who have opted for electrification instead of hydrogen.	Exp 2	KD&CB
#19	Recently, we saw that the hydrogen refining route initially seemed promising, but now a corrective factor of 0.4 has been applied, effectively doubling the required hydrogen input.	HI 3	EI&MS; I&TD
#20	The gas package, spanning roughly 160 pages, outlines regulations for every aspect of gas transport. These rules, originally designed for an established gas network, are now being applied directly to hydrogen, despite the fundamentally different context.	HC 2	RG&S
#21	The government must implement robust and long-term incentive schemes to ensure stability and support sustained progress.	HiP 4	KD&CB
#22	The national government and the European Union have been slow, but it's a challenging puzzle to solve. To their credit, they've worked hard to listen to feedback from producers and potential off-takers, aiming to develop a pragmatic solution that balances the needs of governments, industry, refiners, and producers. However, in trying to please everyone, they often end up frustrating everyone.	HP 2	C&SI; RG&S
#23	A level playing field within the EU would significantly contribute to the stability and predictability of investments, reducing the incentive for industries to relocate to more favourable regions of the world.	HC 1	M&IA
#24	China serves as a compelling example, achieving rapid progress with initiatives such as electrolysis projects. Their structured strategy requires a growing percentage of products, expertise, and components to be sourced domestically, rewarding compliant companies with ongoing subsidies. This model's success lies in the government's active role in market development, as subsidies alone are insufficient without strong commitment and confidence-building efforts.	HI 2	T&TC
#25	For example, connecting an electrolyser to the grid in the Netherlands is currently 150% more expensive than in Germany. These are issues we can address locally.	HI 3	M&IA

Table D.4: Summary of insights from interviews conducted (part 3/5).

#	Instance:	Role:	Theme:
#26	I believe the future lies in a sustainable industrial sector. Without industry, Europe would face significant economic decline, severely impacting our standard of living. While sustainability comes at a cost, that cost must be borne. However, it is crucial that ambitious sustainability efforts do not drive the chemical sector or other industries away. If they find it too expensive here, we risk investments being made outside Europe rather than within.	HI 1	LV&SG; EI&MS
#27	I see the situation in the Netherlands as if everyone is standing hand in hand around a figurative swimming pool, waiting for someone to take the first leap. Only after that first person jumps, others will naturally follow. But right now, in the Netherlands, it has turned into a kind of rat race, where everyone is acting individually.	HC 1	LV&SG
#28	In the Netherlands, the existing gas network operator is rolling out the hydrogen network, largely by repurposing natural gas pipelines for hydrogen use. From both a sustainability and financial perspective, this is a smart move—reducing gas usage while increasing hydrogen capacity. However, it's a complex task, as the phase-out of natural gas and the ramp-up of hydrogen don't always align perfectly, leading to frequent challenges.	HiP 1	C&SI; LV&SG
#29	It is concerning to see that some parties are considering relocating, and in some cases, it's already happening, both in Germany and the Netherlands. This is unfortunate because moving industries elsewhere does not solve the problem of the energy transition. It simply shifts it to another location, potentially making it even more polluting.	HiP 3	LV&SG; M&IA
#30	It's a complete circus of small taxes, innovation subsidies, and countless schemes. Pulling and pushing in all directions, with no single authority or individual overseeing everything simultaneously. The European Commission, national governments, and companies are constantly in dialogue, asking, 'Is this enough? Will it happen?' As a supplier, and primarily a trading company despite now operating our own electrolyser, we are acutely focused on whether the demand is really there.	HC 2	C&SI; RG&S
#31	Once it is clear that tailored agreements (maatwerkafspraken) have been made, it becomes possible to present a project and move forward collaboratively into the next phase. This is how we aim to gradually develop new initiatives. At the same time, our existing business operations, particularly in chemicals, gases, and oil products, continue as usual. These activities remain ongoing and stable.	HiP 3	EI&MS; I&TD
#32	Organisations like McKinsey got their assumptions completely wrong and made everyone believe that green hydrogen would only cost one or two euros more than grey hydrogen. But as projects were announced and reality set in, it became clear that the price gap was far, far larger.	HP 2	EI&MS
#33	The ETS price needs to increase, as this is one of the most significant opportunities to drive change. At the same time, it is crucial to establish a level playing field, ideally on a global scale, although this is very challenging. At the very least, Europe should provide a fair and consistent playing field. Currently, Europe sets certain directives that are then passed down to member states for implementation. However, the flexibility granted to member states in this process creates inconsistencies, making it more difficult for businesses to operate effectively.	HI 2	M&IA
#34	The expansion of industries to other countries is a trend we cannot ignore. For imports, it is crucial to establish stronger, direct point-to-point relationships to ensure stability.	HC 1	KD&CB
#35	The reluctance is worsened by uncertainties surrounding investment horizons and risks. This results in a cautious, wait-and-see approach, whereas decisiveness and a clear vision are essential to drive solutions forward.	sGOV 2	T&TC
#36	To stay competitive, it's crucial to establish strong conditions—such as infrastructure and regulations—that make it attractive for companies to remain and invest here.	sGOV 1	M&IA; RG&S
#37	A viable solution would be for the government to provide either a price guarantee or a volume guarantee. Once a hydrogen backbone is in place, the necessary volumes will naturally follow.	Exp 1	EI&MS
#38	Good infrastructure is crucial for making investment decisions, such as for electrolysers. Many stakeholders are waiting for connections to ensure their products can reach the market. Public investments in infrastructure can have a significant multiplier effect, with one euro of public funding potentially generating ten euros in private investments.	HI 3	EI&MS; I&TD

Table D.5: Summary of insights from interviews conducted (part 4/5).

#	Instance:	Role:	Theme:
#39	I find the H2 Global system to be an excellent solution and bridge the gap. It operates as a double-sided auction: one auction determines the price for supply parties, and another for demand parties, often resulting in a much lower price.	Exp 1	EI&MS
#40	The current approach suffers from siloed thinking and an excessive focus on market mechanisms, with limited proactivity from key players who prioritise investor returns over societal impact. The lack of vision and leadership from the national government, combined with uncertainties around investment horizons and risks, reinforces a wait-and-see attitude. Decisive action and a clear, guiding vision are urgently needed to address these challenges.	sGOV 2	C&SI; LV&SG
#41	The production cost of hydrogen – I could say, yes, it's too high, but of course, this mainly applies to green hydrogen. A significant part of this cost is determined by the price of electricity, specifically green electricity.	HiP 4	EI&MS
#42	The production side is, of course, a different matter. Price considerations and uncertainty regarding demand play a significant role there. This can be viewed as a market-driven aspect.	Exp 1	M&IA
#43	The risks are too great for us to make FIDs, and the lack of clarity in regulations makes it complex for us. We are willing, but not yet able.	HC 2	EI&MS; RG&S
#44	Ultimately, it is the end-user who funds the entire supply chain. If they remain uncertain, it becomes difficult for the rest of the chain to make concrete investment decisions. While progress can be made in terms of engineering and planning, significant investments will only be made if there are sufficient binding contracts in place that allow development and guarantee the use of the infrastructure.	HiP 5	T&TC
#45	We could implement a similar model to China's, ensuring that electrolysers are scaled up and utilised effectively. We need to start implementing and using these technologies. Several stakeholders I've spoken to believe that this approach could help drive costs down over time.	HI 2	M&IA
#46	What we observe as the first step in the point-to-point approach towards end markets involves parties already using ammonia today. This means ammonia is stored, and we develop infrastructure around it. Whether this will involve low-carbon, clean, or green ammonia is still to be determined.	HiP 5	I&TD
#47	However, this must be supported by the right incentives. The government needs to take on a coordinating role and provide these incentives, which is why a long-term perspective on schemes like SDE++ is essential. Consistency is equally important—a reliable government is crucial. Tailored agreements will also play a key role in this process.	Exp 1	KD&CB; T&TC
#48	In this context of uncertainty, it becomes even more challenging to commit. Developing business cases for projects like electrolysers is already a complex task, let alone when there is no clarity about timelines or conditions.	HI 4	T&TC
#49	It's become somewhat typical of the Dutch government to announce initiatives, set things in motion, and then abruptly reverse course, leaving stakeholders uncertain about what to expect. This is something we see not only in the Netherlands but across Europe to some extent. Clear regulations and consistency are crucial—knowing that a €100 million investment is a sound choice would make a significant difference. Introducing measures like purchase obligations is, I believe, a positive step in the right direction.	HI 3	RG&S; C&SI; T&TC
#50	Take the coal-fired power plants, for example. Initially, they were asked to scale down operations, which they did. Then they were informed they must shut down entirely by 2030, even though their depreciation periods extend far beyond that. Understandably, this undermines trust for such stakeholders that have an important role right now.	HI 2	T&TC
#51	The cancellation of the DRC has weakened trust across the entire supply chain. For Rotterdam, this figuratively places us in an 'island mode,' which is problematic as it removes a critical link in the network.	HC 1	I&TD
#52	The transition is progressing very slowly, and there are several reasons for this. One key challenge is the inconsistency of government policies. With each new development, existing plans are often discarded, which hinders progress.	Exp 3	T&TC

Table D.6: Summary of insights from interviews conducted (part 5/5).

#	Instance:	Role:	Theme:
#53	There appears to be a lack of vision and responsibility from the national government, which is concerning as it should take a leading role in addressing complex challenges.	sGOV 2	T&TC
#54	As far as I'm concerned, they can go. I don't think they should leave the EU, but we should try to perhaps establish production in Spain or Italy instead. If they can manufacture iron there while still being able to compete with Asia—China in this case—or the United States, that would be important in my view.	Exp 3	EP&PD
#55	Well, what the Netherlands and Europe are doing—and what is very beneficial—is the introduction of the Gas Directive and the Gas Regulation, which establish rules for grid management. That is absolutely crucial, and it has been handled very well. Europe acted quickly on this, partly due to pressure from us and the Germans. The key questions now are: how will these grids be financed? What is allowed in terms of state aid? What tariff structures apply to ensure that construction can actually take place? After all, these grid operators…"	sGOV 3	EP&PD

D.5. Attachment: Summary overview of interview instances

On both the next page and the separate attachment, an overview of the instances supporting both the Findings (Chapter 6) and the Discussion (Chapter 7) is provided. As this overview is in A4 format, it is advisable to display the A3 attachment on a separate screen or have a printed copy alongside the report while reading Chapters 6 and 7. This file contains references cited (*[#XX]*) in both chapters, assisting in clarification and improving understanding, serving as an alternative to the extensive Table D.2 presented earlier in this appendix.

Summary overview of interview instances

This frame provides a structured and visual representation of the most relevant and frequently referenced excerpts from the interview transcript analysis. It serves as a supporting tool for readers when navigating Chapter 6: Findings and Chapter 7: Discussion. Within the Discussion chapter, direct references are made to specific quotes, which are presented in this format to enhance clarity and accessibility. By presenting the information in this structured manner, the frame aims to make complex insights more accessible and to facilitate a deeper understanding of the key findings and discussions within this thesis.

The quotes are categorised according to their primary second-order theme, offering a thematic structure to the analysis. While some quotes may relate to multiple themes, this categorisation ensures a clearer overview, making it easier to identify key insights. Each quote is assigned a reference number [#XX], which corresponds to its mention in the discussion text, allowing for seamless cross-referencing. Additionally, the stakeholder group associated with each quote is explicitly mentioned, providing context on who contributed to each perspective.

On the right-hand side, the stakeholder groups and second-order themes are explained in further detail. To improve readability, colours are used to indicate the specific stakeholder group from which each quote originates. This colour-coding helps to quickly identify different viewpoints and their sources. Further, to the far right, an overview of the Findings figure is included. This figure provides a visual representation of the identified regulatory voids and offers a simplified overview of the current supply chain development within the hydrogen transition. This figure can be found in Figure 6.1 on page 56 and serves as a reference point for understanding the broader context of the discussion.

Table 5.3 (page 52): An overview with the explanation of the second order terms.

Second order theme	Abbreviation	Explanation
Regulatory Guidance & Standardization	RG&S	Relates to the regulations and standards that are in place related to the industry development.
Trust & Transparency Creation	T&TC	Concerning the trust development and the transparency between different industry parties and government bodies.
Cooperation & Stakeholder Integration	C&SI	Interaction and cooperation between the various stakeholders that are concerned with the hydrogen development. Also, the integration of the stakeholders within the system is regarded.
Economic Incentives & Market Stimulation	EI&MS	Stimulation and economic incentives that are developed and implemented in the system or should be implemented.
Knowledge Development & Capacity Building	KD&CB	Relates to the development of new techniques and the capacity that is needed for the developing technology to gain momentum.
Infrastructure & Technology Development	I&TD	Concerning the technical and infrastructural (when needed) aspects of the hydrogen technology adoption and development.
Long-term Vision & Strategic Goals	LV&SG	Strategic goals and long-term visions are set by government bodies, industry parties themselves, society and other individuals.
Market & Institutional Adaption	M&IA	Concerning the development market structure and the institutional and organisational set-up/adoption that needs to be in place.
External Pressures & Policy Drivers	EP&PD	Pressure from among others society, governments or industry parties that have the desire to make the technology adoption happen.

Stakeholder group	Abbreviation	Explanation
(Semi-)Government	sGOV	Governments (ministries), government-related actors (Gasunie) and EU-level of government.
Hydrogen Producer	HP	Actors at the frontend of the supply chain responsible for the production of hydrogen (e.g.: building electrolysers).
Hydrogen industry Provider	HiP	Involved actors that are providing (temporary) storage or transport options other then pipelines.
Hydrogen Consumer	HC	Back end of the supply chain that consumes hydrogen; e.g.: steel plants, chemical industries, and fertiliser production.
Expert	Exp	Academical or hydrogen transition experts that do not have an active role in the current hydrogen transition.
Hydrogen Importer	HI	Companies that focus on the import of hydrogen; e.g.: the Port of Rotterdam or North Sea Port.

Table 3.2 (page 34): Overview of desired interviews per stakeholder involved.

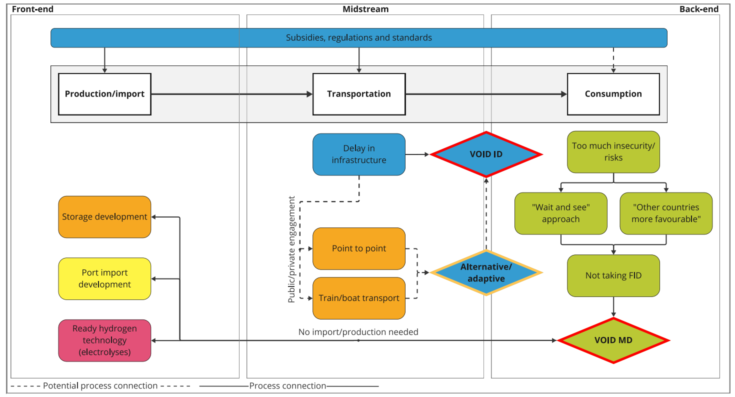

Figure 6.1 (page 56): Status quo of the hydrogen supply chain development with regulatory voids (blue = (semi-)Government, green = consumer, orange = industry provider, pink = producer, and yellow = importer) (made by author).