System Transitions through Path Creation – A Company Perspective

Master Thesis – Management of Technology

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MANAGEMENT OF TECHNOLOGY MASTER THESIS

System Transitions through Path Creation - A Company Perspective

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Executive Summary

Climate change is difficult to mitigate in industries that have originated from, and developed through fossil-based hydrocarbons. These hard-to-abate industries require more than top-down policy-making to reach the decarbonisation goals. In this thesis, the focus is laid on the company's perspective to organise and steer the transition. Focusing on Rotterdam's petrochemical cluster, the thesis attempts to answer the following question:

"How can companies organise for path creation, and drive its development in the petrochemical industry under a transitioning environment towards low carbon hydrogen?"

A conceptual framework is made out of two existing theories: The Technology Innovation System Framework (TIS) and the Path Theorem. The synthesis of these two constructs lay the foundation of this research.

- **Technology Innovation System** - Evaluating the current, and desired system through seven building blocks and their influencing conditions, diagnosing the performance and stability.
- **Path Theorem** - The path dependency, creation and development constructs are integrated to explain how the cluster's industry dynamics favour the status-quo, and block the development of the desired system.

Through an exploratory qualitative case study, data is collected through literature research and five semi-structured interviews. An iterative learning process is applied, cycling between the literature research and interviews to validate and refine results. The research lead to the following key findings:

1. **Incumbent Oil & Gas TIS entering decline** - High techno-economic maturity is offset by eroding competitiveness. Volatile, and rising energy/feedstock prices, ageing assets and rising carbon taxes can not compete against cheaper and modern overcapacity from Asia and the Middle East. The industry invests in short-term, site-level energy-efficiency upgrades as the regulatory landscape attempts to squeeze out the status-quo, further destabilising the system.
2. **Low-carbon hydrogen TIS in early-stage, but exhibits potential** - Hydrogen possesses a great variety of known technological applications and is a well understood element. The regulatory landscape, whilst discouraging the status-quo, is in a too fluctuating and volatile state to establish a healthy investment climate. Additionally, current production, and backbone infrastructure are lacking; Domestic electrolysis target not close to being reached, and the HyNetwork pipelines has been postponed beyond 2030.
3. **Paradoxical Interdependence industry dynamic locks the cluster.** - Intensive physical interconnections between firms are present in the cluster, yet remain strategically isolated; no shared long-term cluster vision emerges. Three self-reinforcing mechanisms are identified underlying this dynamic, characterised by a triangular interconnection negatively influencing the *Network formation and coordination* building block.

The study then formulates two path creation propositions, selecting the *Network formation and coordination* building block as the strategic leverage point. The two path creation initiatives are named 'Cluster Billboarding' and the 'Industry-Authored Roadmap'. These undertakings create the social glue required to coordinate organisational resources into powerful network- and system resources, breaking away from the three reinforcing mechanisms.

- **Cluster Billboarding** - Actively advertising and incentivising the vision of the PoR becoming Europe's Hydrogen hub will attract external market actors towards the cluster. The like-minded entrants build a coordinated vision, generating network reputation and collective expectations which empower collaborative initiatives and enable network effects. Facilitating strengths of the Port's authority can smoothen entry and accelerate the network formation.

- **Industry-Authored Roadmap** - A bottom-up roadmap, drafted by operating companies, utility providers and knowledge institutes help build lacking social capital within the cluster, whilst closing the gap between policy-makers and the industry. Iterative revisions enable learning, and help further reduce policy friction.

This research has evaluated the cluster's status regarding the energy transition. The evaluation highlights the necessity of a healthy investment climate, constructed by effective regulations and policy-making. The transition challenge is more so organisational than technological. In the study, awareness is raised for the agency companies can have. This agency is shown in the proposal of potential ways to develop network formation and coordination from a bottom-up perspective.

Preface

In front of you lies the thesis: *"System Transitions through Path Creation - A Company Perspective"*. The contents of this report represent the accumulation of competencies which have been gathered over the course of 8 years. While many of these competencies are highlighted through the following pages, reading between these lines will bring you, my dear reader, and me closer together.

Over the last 8 years I have learned many things. Some of which were learned inside of knowledge institutes, while many other aspects were experienced outside of said institutes. During my academic career I first learned that Applied Physics was not for me. The following four years of obtaining my bachelor in Mechanical Engineering has taught me that I am purposed for leaving this world at least a little better than that I found it. As a graduated mechanical engineer, I can now stereotypically help stranded co-students with defect bicycles outside of the faculty. Meanwhile, inside the faculty of Technology, Policy and Management, the ambition for a greater purpose was sought after.

Climate change is a wicked problem, consisting of a dazzling amount of social, technological and economical variables. Some of which are understood, some of which aren't, and some of which are still unknown. Many nations, organisations, and thus people, worldwide are attempting to solve this problem. Equations are being solved, solutions are being designed, and risks are being taken to better understand, and ultimately combat climate change. I hope to contribute, as part of the people, through conducting this study.

I would like to thank Roland for his unwavering support in both me as a person, and the research project. While I believed my talent for research was subpar at most, you continuously encouraged me, allowing me rise above myself whilst also staying true to our collective academic goal of the project. I am also grateful to Zofia; your eye for detail gave constructive feedback on the finest points, whilst warm-heartedly connecting me to relevant colleagues. Additionally, I would like to thank all interview participants for their energetic dialogue and discussion, contributing significantly to this research. Finally, I would like to thank my dear friend and housemate, Sander, for accompanying me to the faculty every day, and the 32nd board of the student association *Curius* for always welcoming with me open arms and having a hot cup of coffee at the ready.

May this report offer you useful insights, and bring us one step closer to successfully protecting the planet.

Fred Dirk Bruining van Dongen

Delft, 19th June, 2025

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"We are called to be the architects of the future, not its victims."

-Fuller R. Buckminster (1982)

1 Introduction

1.1 Context

In 2015, 196 parties to the United Nations signed the Paris agreement, stating their goals to 'keep the global average temperature well below 2 ° C above pre-industrial levels' and to pursue efforts 'to limit the temperature increase to 1.5 ° C above pre-industrial levels'(2015). Above these temperature levels, many significant problems will arise; sea levels will continue to rise, food and water security becomes vulnerable, and international political conflicts, besides other problems are to be expected (Trenberth, 2011). To limit the global warming to 1.5°C, the European Union has set a reduction target for their member states of 55% in GHG-emissions realised by 2030, and reach net zero (100%) by 2050 compared to 1990 emission levels (European Union, 2023).

The main driver of climate change is greenhouse gas emissions. CO2 emissions account for 74% of these emissions (Filonchyk et al., 2024). As different countries produce different amounts of emissions, the agreement establishes Nationally Determined Contributions (NDC's) per signed country. A nation's contributions are linked to their emissions and their ability to reduce them (UN, 2023).

In industries that are hard to abate, this means that a transition is necessary from fossil fuels to alternative options. These alternatives are relatively new and are becoming viable due to various policies being implemented. These policies are targeted at making low-carbon alternatives more attractive, whilst discouraging the persistence of the status-quo. However, the future of these policies is unstable because of changing political compasses in political structures, resulting in uncertainty for investments supporting the transition (Ivanovski and Marinucci, 2021). An example of this volatility is the Trump administration's announcement that the United States will exit the Paris Agreement (The White House, 2025). In Trump's previous term of office (2017), this same feat was attempted but failed (Pullins and Knijnenburg, 2025). Just attempting to exit the agreement signals major uncertainty towards the industries, influencing decision-making processes.

One of the most challenging industries to decarbonise is the petrochemical industry (UNFCC, 2023). Its key challenges are outlined below.

- The energy-intensive nature, requiring very high temperatures for the chemical processes. These production plants operate on a continuous basis, requiring a constant and uninterrupted supply of energy, for which fossil fuels are the optimal choice. Other processes on the production plant are on a batch production basis, requiring large amounts of energy at inconsistent timings. Energy availability is essential for the efficiency of a petrochemical plant.
- Feedstock requirements - hydrocarbons are used as input for the chemical processes to produce petrochemicals, often producing a by-product containing carbon.
- Extensively developed infrastructure and supply chains for current process operations, resulting in long asset life cycles, high sunk costs and high switching costs.

One of the decarbonising alternatives to fossil fuel based processes of the petrochemical industry is hydrogen. Hydrogen has been a key input material for the industry since the early twentieth century, being used for petroleum refinement and ammonia production (Smil, 2010). Currently, this hydrogen is produced using fossil fuels as a feedstock, which in the process emits CO2 in doing so. This type of hydrogen is known as grey hydrogen. Hydrogen, however, has more potential than just its feedstock application alone.

Besides using hydrogen as a feedstock material for the chemical processes, the element has characteristics which prove useful in other functionalities. It can be combusted, and thus can be used directly as fuel. Furthermore, hydrogen can be produced by electrolysis, using water and electricity, which can be produced from renewable sources. Renewable energy sources such as wind and solar are at the core of the energy transition as a whole. However, one of the main challenges is the intermittent nature of these sources; there is not always wind, nor sun. Because of the intermittent nature of green energy sources, hydrogen produced by renewable energy via electrolysis, known as green hydrogen, can be used as an energy carrier.

Nevertheless, the adoption of hydrogen in the petrochemical industry proves to be a challenge; The International Energy Agency states the industry is not on track to reach the Net-Zero Emission scenario, requiring acceleratory measures (IEA, 2023). Large-scale projects are being postponed and cancelled because of incompatible policies and immature markets (HyCC, 2023) (Burgess, 2024) (Jetten, 2024). Additionally, BP has shutdown 18 early-stage green hydrogen projects in response to the company's weak quarterly profits (Dokso, 2024). Geopolitical and macro-economic forces are inhibitive factors for the transition to low carbon hydrogen.

Because of the time pressure that the climate crisis possesses, these postponements and cancellations are endangering reaching the goals formulated in the Paris agreement. According to the European Environment Agency, the current climate commitments project a 48% emission decrease by 2030 compared to 1990 (2024). This means there is still a 7% gap to bridge by 2030 for the EU. Current attempts of adopting technologies in large scale setting are inadequate, and fail to be nurtured through the infant stage. Acceleration of emerging innovation needs to happen to support broader system transition, and reach the set climate goals (Markard et al., 2012).

1.2 Problem Focus

As stated previously, the petrochemical industry is hard to abate because of the inherent characteristics it possesses. Agencies and governmental bodies steer towards the mass adoption of green hydrogen in the industry sector as a major contributor to the decarbonisation (Hellinga and Van Wijk, 2021). However, projects developing the hydrogen value chain are facing cancellation and postponements. Market actors state the present uncertainty and immature, volatile market conditions inhibit developers from green-lighting low-carbon hydrogen projects.

Most of these projects are carried out by established oil and gas companies. Over time, these companies have developed significant infrastructure and business models focused on fossil fuels from the start (Weetch, 2022). It is difficult for new actors to enter the industry due to the high sunk costs involved. Additionally, the fossil fuel sector's long-term growth and its resistance to change have led to institutions and society co-evolving, heavily relying on the current situation (Seto et al., 2016).

1.3 Goal

In this research, the goal is to explore how the system transition from a fossil-based system to a hydrogen-based system can be supported from a company's perspective in the petrochemical industry. This exploration combines two theoretical frameworks: Technology Innovation Systems and The Path Theorem. Both these theoretical frameworks are explored and defined in section 3. The research aims to be valuable both academically and practically by applying and operationalizing the theories in a transitioning environmental context.

1.4 Research Question

Extensive research has focused on policy making in the energy transition. However, while policy can guide an industry, transformation must come from within. Consequently, the viewpoint of the company holds significance too. There is a lack of research that attempts to take the company perspective (Köhler et al., 2019). This research aims to contribute to a more effective system transition within the petrochemical industry by incorporating the company perspective. Accordingly, the following research question is formulated:

"How can companies organise for path creation, and drive its development in the petrochemical industry under a transitioning environment towards low carbon hydrogen?"

Because of the concepts that are included in this research question and the complex nature of the question, a conceptual literature review (section 3) is first performed before formulating the sub-questions (subsection 3.5).

1.5 Scope and Perspective

As explained in chapter 1, the development of the renewable hydrogen value chain must be accelerated to reach the climate goals set for 2030 and 2050. This challenge has been studied extensively from a top-down point of view, mainly advising policy-makers (Bergek et al., 2008) (Köhler et al., 2019). This research will adopt a bottom-up approach, focusing on the perspective of a company or market actor. This will help to better understand the challenges that hinder the development of a low-carbon hydrogen system.

This study examines firms involved in the advancement of the hydrogen value chain. The hydrogen market is still in its nascent stage, primarily relying on the alignment of supply and demand. Without consumer guarantee, producers are hesitant to manufacture. Therefore, achieving market stability necessitates coordination and partnerships among the sector's players. Like these companies, this study needs to consider the market dynamics. This is why the analysis is positioned at the meso-level, focusing on a significant industry cluster in the Netherlands, specifically the petrochemical industry in the Port of Rotterdam.

The industry cluster located in the Port of Rotterdam is one of 6 clusters located in The Netherlands. The cluster is one of the largest industrial clusters in Europe by land area, economic output, and industrial capacity. Its vast size, infrastructure, and economic impact make it a cornerstone of Dutch and European industry. The cluster comprises 120 industrial companies, including 45 belonging to the chemical industry and 4 to the refining sector (Port of Rotterdam, 2025b). The industry in the port emitted 20.3 megatons of CO2 in 2023, accounting for nearly 14% of the national total (Kampman et al., 2025).

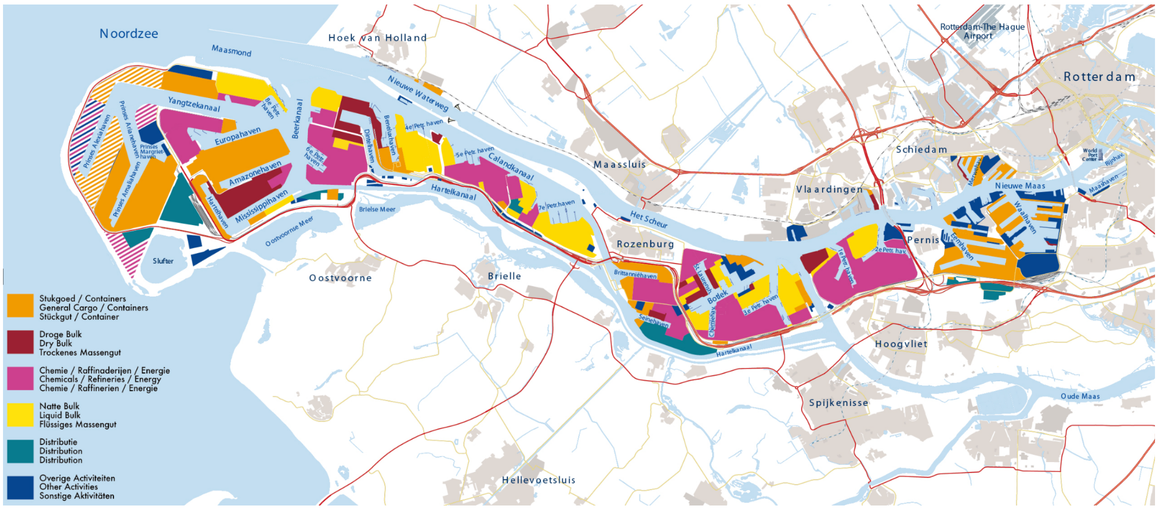

Figure 1: Colour coded map of the Port of Rotterdam (Port of Rotterdam, 2025a)

The research question examines the company's perspective. Therefore, the analysis at the meso-level is translated into a micro-level view. This view focuses on specific elements that are practical for the study's unit of analysis. To efficiently explore the meso-level, and smoothly translate the meso-level analysis to the micro level, the Technology Innovation System framework is adopted in this study. The definition of the framework and the functionality in this study is described in subsection 3.3. A visual conceptual representation of the different levels is shown in Figure 2.

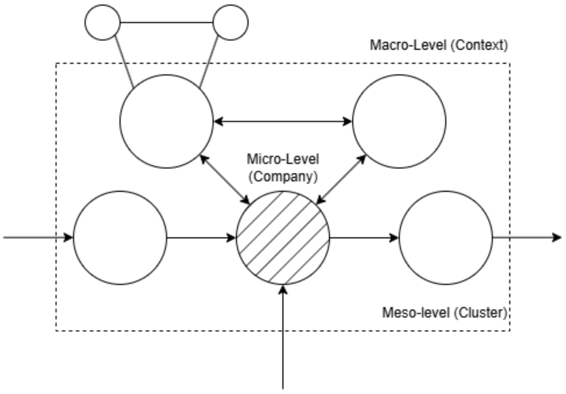

Figure 2: Visual presentation of the micro, meso and macro scale in this research.

1.6 Link to the MSc Management of Technology Programme

This thesis, whilst attempting to generate both academic and practical value, is written to prove the competencies taught throughout the master programme Management of Technology (MoT). The study explores the energy-transition of a hard-to-abate industry through the company perspective. The Technology Innovation Framework is used to analyse both the current state of the focal industry, and the desired state. This evaluation generates insight on the meso-level technology dynamics of two technology product groups. Additionally, the company focus highlights the corporate values and prerequisites of large-scale diffusion of emerging clean technologies.

The addition of path dependency, creation and development enable the analysis of the dynamics present, which generate barriers or drivers for TIS-development. The path creation construct allows for global propositions on strategies to overcome these barriers or benefit from the identified drivers. Combining these analyses from a company perspective leads to empirical insights and strategy propositions that are highly relevant to the MoT program.

1.7 Societal Relevance

The practical value of this research lies in its applicability to companies, policymakers and other stakeholders in the hydrogen value chain and energy transition initiatives. While propositions for policy making are relatively abundant, the company perspective is often overlooked in academic research. The empirical analysis of the current status of the incumbent system and the desired, hydrogen-based system, a bottom-up perspective is showcased. This perspective gives the opportunity for a better mutual understanding between policy-makers and industry. By identifying the industry dynamics at play in the focal cluster, this understanding is enhanced, whilst also describing the mechanisms that could block or drive development of the energy transition. Strategies are then proposed originating from the inhibiting mechanisms at play to overcome these barriers. This study thus aims to provide companies with tools to help align with the set decarbonisation goals.

1.8 Reading Guide

This report is set up to be read sequentially. section 1 provides the introductory context of the research, explaining its relevance, focus, and scope. section 2 moves on into more detail on the scope, exploring the petrochemical industry located in Rotterdam. Having described the challenges that this industry face in tackling the decarbonisation goals, section 3 moves on to the conceptual literature review. This review explores and defines the theoretical concepts used in this research. section 4 contains the research design, explaining what data collection methods are used and how this data will be analysed. section 5 introduces the first analysis part, evaluating the status of two systems. The second part of the analysis is done afterwards, in subsubsection 3.2.1, identifying dynamics which act as barriers to development of a system, or as a driver. With the systems mapped, and the dynamics uncovered, strategies are formulated in section 7 that try to deviate from the current system. Then, an answer is given to the research question in section 8. Lastly, points of discussion such as limitations, assumptions, and future research are stated in section 9.

2 Petrochemical Industry of Rotterdam

The petrochemical industry produce chemical products from oil and gas feedstocks (Zhang et al., 2023). The industry generally focuses on refining hydrocarbons into base chemicals which serve as essential feedstocks for products such as plastics, fertilizers and pharmaceuticals. In 2018, the petrochemical industry produced 85% of the base chemicals used as feedstocks in the chemical industry (International Energy Agency, 2018). The general value chain of the petrochemical industry sector is shown in Figure 3.

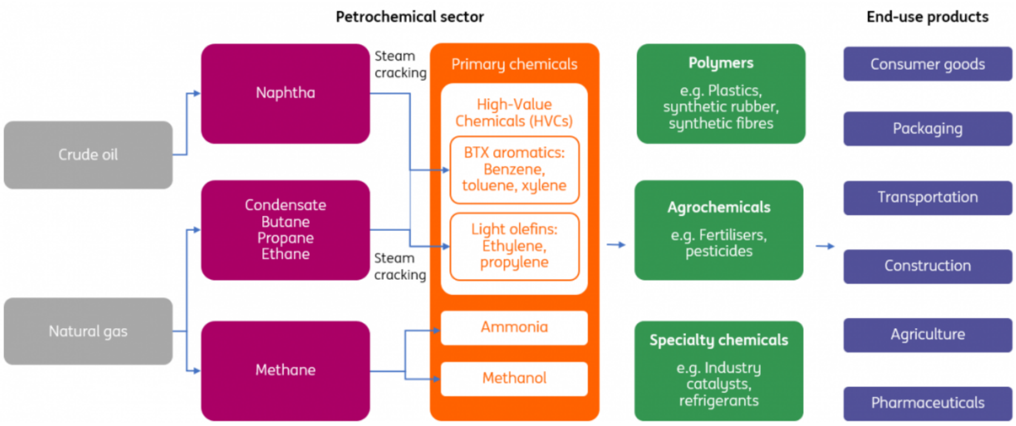

Figure 3: The petrochemical sector value chain (Zhang et al., 2023).

These hydrocarbons are currently primarily fossil-based, refining and cracking crude oil and natural gas. The petrochemical industry originally utilized waste streams from the fuel refining sector, repurposing them into higher-value products. In this research, the fuel refining and petrochemical industries will be considered as an integrated system. This choice reflects the structure of the targeted cluster where refining processes and petrochemical processes are integrated in the refinement plants.

The Port of Rotterdam hosts four refinery plants that collectively process over 53.6 kilotons of oil, resulting in CO2 emissions of 9.2 megatons (Oliveira and Schure, 2020)(Port of Rotterdam, 2023). These emissions account for 45% of the total emissions within the Port. Given the Netherlands' annual CO2 emissions of 156.1 million tons, the refinery plants in the Port of Rotterdam contribute approximately 5.9% to the national total (Tiseo, 2024). Moreover, over the past seven years, refineries within the industrial area of the Port of Rotterdam have achieved the smallest reduction in emissions, shown in Figure 4 (Kampman et al., 2025). This situation underscores the crucial role of the petrochemical sector in the decarbonisation effort.

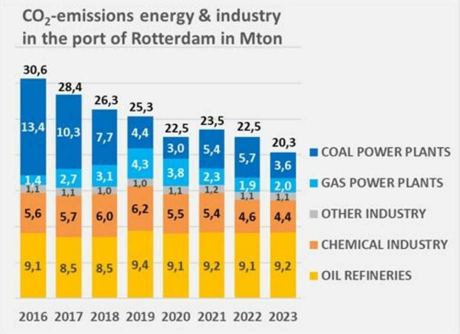

Figure 4: CO2-emissions by energy and industry in the Port of Rotterdam (Kampman et al., 2025).

2.1 Hard-to-abate Industry

As shortly described in subsection 1.1, the petrochemical industry is hard to decarbonise because of the energy intensive nature, feedstock requirements, and the incremental infrastructural developments made. Additionally, the infrastructure has long depreciation life-spans, creating smaller replacement windows in which low-carbon alternatives can be considered. In this section, the hard-to-abate nature of the industry in focus is further explored.

The petrochemical processes in the industry regularly require high temperatures. To achieve this, fuelgas is combusted. These fuels are mainly fossil-based, and amount to almost 85% of the total emissions (International Energy Agency, 2018). The other main source of the industry's carbon footprint is the process-related emissions. The sector uses hydrocarbons as feedstock in the processes, thus incorporating carbon in the final product. Whilst this is an advantage for the sector as the carbon is not emitted directly, these are still indirect emissions, worthy to be considered.

The direct, and indirect emissions are categorised through the Greenhouse Gas Protocol (GGP) (Ranganathan et al., 2004). Direct emissions originate from sources owned or controlled by an organisation. Fuel combustion in furnaces, and chemical processes resulting in greenhouse gases are examples of this. Indirect emissions occur as a consequence of an organisation's activities, yet the organisation does not own or control the emitting source. The GGP uses three scope levels to gauge the emissions of a company. Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Finally, scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions. The scopes are visualised Figure 5.

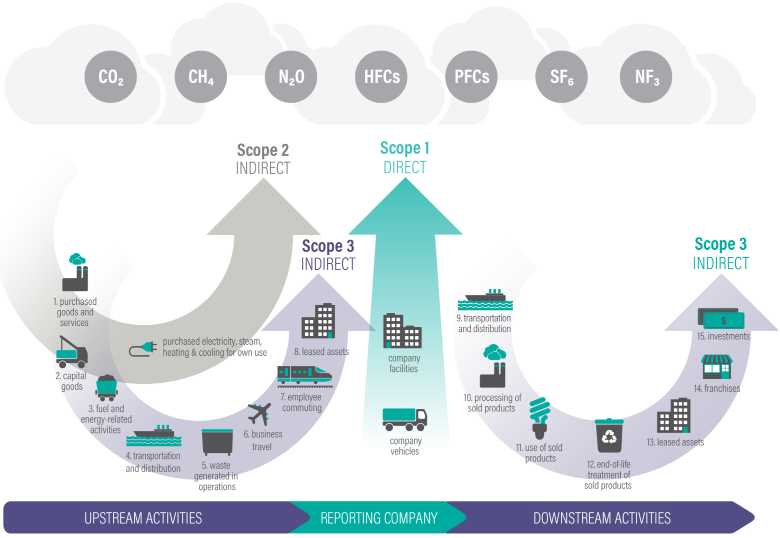

Figure 5: The three scopes of greenhouse gas emissions visualised (Ranganathan et al., 2004).

2.2 Decarbonisation options

For this research, it is important to look beyond the focus of low-carbon hydrogen and take the other options into account. The Dutch Environmental Assessment Agency (PBL) has categorised seven categories of decarbonisation (Oliveira and Schure, 2020), visualised in Figure 6. The possible options are described per enumerated decarbonisation category.

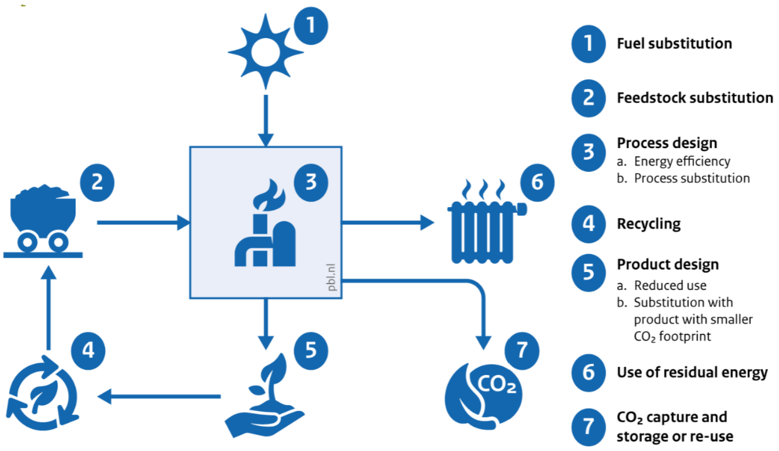

Figure 6: Decarbonisation options for the petrochemical industry

1. **Fuel substitution** - The petrochemical processes currently rely on fossil-based fuels to generate the industrial heat necessary for their processes. Electrification or low-carbon hydrogen can substitute the energy needs of various petrochemical systems.

   As most of the direct emissions of the petrochemical industry are due to thermal processes, fuel substitution has a major decarbonisation potential. Mainly gas-fired furnaces and steam-generation systems are targets for fuel substitution because they require the most thermal energy.

2. **Feedstock Substitution** - Replacement of the hydrocarbon-based input materials for low-carbon alternatives reduces the process emissions. Bio-based feedstocks, low-carbon hydrogen are examples of low-carbon alternatives.

3. **Process design** - Rethinking the process design in terms of decarbonisation refers to the energy efficiency of the process, and substitution of the process towards more sustainable ones.

   Energy efficiency upgrades on existing assets do not, however, eliminate carbon dependency. The incremental innovation processes may result in a larger gap between emerging sustainable processes technologies and the incumbent processes used. This gap is created through performance, sunk costs and the missed learning effects (Janipour et al., 2020). Whilst a short-term solution for quick decarbonisation gains, it may hamper reaching the deep decarbonisation goals envisioned for 2050. Energy efficiency through electrification with high COP technologies such as heat pumps do however offer a long-term solution (Stork et al., 2018).

   Substituting the incumbent process with a more sustainable alternative is interrelated to feedstock substitution. The implementation of biomass as sustainable feedstock consequently needs the pyrolysis process in order to create biofuels.

4. **Recycling** - Recycling is essential to create a circular economy. Instead of generating waste, this waste is re-used in a effective way, allowing for the production of more with less. The petrochemicals refined by the industry are needed for the production of a wide variety of end-products. Plastics, rubber and synthetic fibers are examples of end-products based on petrochemicals.

The recycling of these end-products reduces waste, such as plastic pollution. Whilst these types of pollutions are not CO2-emission based, plastic pollution is a danger to animal life, and other environmental elements (Hammer et al., 2012). Chemical recycling processes such as plastic pyrolysis can be used to create pyrolysis oil, which can be processed into a new, more sustainable feedstock stream (Dai et al., 2022). Recycling is thus interrelated to process design and feedstock substitution.

5. **Product Design** - As mentioned above, recycling can create positive economic value as less is used to create more. With product design, incumbent product functions can be replicated by selecting more sustainable materials. Product design is closely related to process design; switching to bio-based feedstocks requires a retrofit of the refining process (Bhatt et al., 2020).

6. **Use of residual energy** - The residual energy of the energy-intensive petrochemical processes can be used for domestic heating surrounding towns and cities. However, it is important that the transporting distance remains short, in which large volumes of energy can be transported. This is because of the efficiency loss in the heat grid.

7. **CO2 capture and storage or re-use (CCUS)** - Capturing and storing or re-using the CO2 emitted by the petrochemical processes can greatly reduce the emissions of the industry. Carbon can be captured pre-combustion and post-combustion, either CO2 absorption of the fuel gas, or by absorbing the CO2 of the resulting flue gases.

2.3 Hydrogen in the petrochemical industry

Hydrogen has played a critical role in petrochemical processes before obtaining the role as enabler of the energy transition. The element was introduced for producing ammonia and methanol. Later, hydrogen has been used as a reactant in many (petro)chemical reactions. Global production of hydrogen amounts to 90 Mton/year (IEA, 2023). 96% of this production amount is gained through the use of fossil feedstocks (Dulian et al., 2025). Although hydrogen can be produced through coal and oil, steam methane reforming (SMR) using natural gas is the preferred process as it is the most economically profitable. The efficiency of a high efficiency steam reformer is about 80%, with CO2 emissions being around 0.9 kg per Nm3 H2 (Mosca et al., 2020).

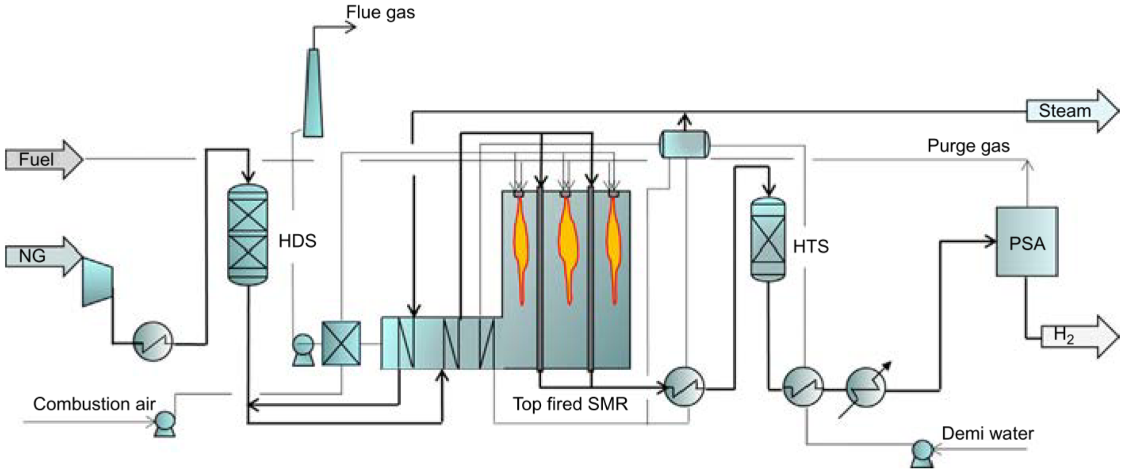

Figure 7: Simplified process flow diagram of NG steam reforming for pure H2 production (Mosca et al., 2020)

Hydrogen already has a foothold of applications in the petrochemical industry. In addition to its role as a production and reactant, it could also fuel energy-intensive processes. Currently, hydrogen is mainly produced through steam methane reforming, which relies on fossil feedstock. Alternative, sustainable hydrogen production processes must be adopted for decarbonisation. Low carbon hydrogen can be obtained through electrolysis using sustainable electricity, or by implementing CCUS to capture the CO2 emitted by SMR.

Hydrogen can provide major decarbonisation in the sector through fuel substitution and feedstock substitution. Applying low-carbon hydrogen as fuel for processes that currently use gas-fired equipment (distillation, cracking processes, reforming) reduces the CO2-emissions produced through combustion. The ’mission possible’ roadmap for industry decarbonisation forecasts a 7-11x demand increase (UNFCC, 2023). This increase shows the significant role low-carbon hydrogen has in the decarbonisation of the industry. How hydrogen can play the protagonist in decarbonisation efforts is envisioned through different roadmaps and strategies, of which examples are given in overviewed in appendix subsection A.1.

3 Conceptual Literature Review

3.1 Introduction

The purpose of the literature review is to collect existing knowledge on the research question, explaining the definitions of concepts used. First, the theoretical background of the most important concepts that underlie this research is given. The literature research explores the connection between each concept and the study's scope, highlighting the contribution of these concepts to the research. Then the concepts are synthesised in subsection 3.4. To conclude, the sub-questions are formulated in subsection 3.5.

3.2 The Path

The collective term *'The Path'* is minted for this study to incorporate the three constructs; Path Dependency, Path Creation and Path Development in a single term. Additionally, the contribution to this study made by the three constructs represented by the Path is described in this section. Finally, the synthesis, or combination, of the constructs used in this study is argued for.

Some of the hard-to-abate characteristics of the petrochemical industry are of historical nature. These characteristics have been reinforced over time by incumbent industry dynamics. Mechanisms such as incremental innovation and system integration result in high sunk costs and switching costs (David, 1985). Additionally, the industry's assets have long depreciation cycles of 20-30 years (Janipour et al., 2020), which create scarce decision-making windows. This scarcity also contributes to the industry's difficulty in abatement. To better understand these characteristics, and initiate path creation, the path dependency of the focal petrochemical cluster is important for this study. The core concepts of Path Dependency, Path Creation, and Path Development are explained to provide insight into the mechanisms of each concept in a technological system context.

3.2.1 Path Dependency

Path Dependency describes the influence that past events and decisions have on constraining the events and decisions in the present and future. Path dependency was conceptualised by David and Arthur to critique neo-classic economic theories, which assume that the chosen technology or structure is optimal by definition (1985) (1994). Instead, they argue that the dominant technology or structure does not have to be the optimal one, stating that the development of the structure or technology can be subject to contingent events early on, which enable self-reinforcing processes that lead to very different outcomes later in time.

The contingent nature of path dependency refers to the unpredictable events which can influence the path's trajectory (Vergne and Durand, 2010). It also refers to deliberate choices made in an unpredictable context (David, 2000). Early on in the path, this contingency affects the decision-making, resulting in the adoption of a certain technology over another. Specific events can thus result in a completely different outcome down the line compared to if the contingency did not occur. Early on, these events have the ability to create a butterfly effect[1]. Later on in the path, a contingent event can shock/influence the incumbent system in a way for it to unlock the present rigid, dominant structure, allowing structural change.

Self-reinforcing mechanisms are processes that have positive feedback attributes, increasing the momentum of an emergent path trajectory until it ultimately becomes the dominant structure. A dominant structure refers to a situation in which other emergent paths are no longer valid choices. The dominant structure is also known as a "Lock-in". The lock-in phenomenon is further explored later in this chapter.

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[1] The butterfly effect refers to the phenomena describing the sensitivity a system's state can have on small initial conditions over time (Lorenz, 1972).

As mentioned earlier, the locked-in situation does not mean it is the most efficient or effective one. The technological lock-in of the QWERTY lay-out is an classic example of this - To address the problem of jamming typewriter keys, the QWERTY-layout was designed and implemented to minimize the chance of two letters being adjacent to each other while typing, which created the jamming problem. Sometime later, after the jamming keys were resolved by moving onto a different structural mechanism. The QWERTY-layout was no longer necessary as the original reason to adopt became obsolete. However, the QWERTY-layout persisted. David described three main influences; (1) compatible and complementarity nature of technology, (2) increasing returns to adoption and (3) difficulty of asset redeployment for alternative use (1985). The technological lock-in became apparent later, when the developed DVORAK lay-out allowed for more words per minute typed than QWERTY. However, the earlier adoption of QWERTY lay-out throughout the market inhibited the DVORAK lay-out to become the dominant design. In this research 4 types of increasing returns to adoption are distinguished (Janipour et al., 2020).

- **Economies of scale** - By increasing the production volume, the fixed production costs are spread over a larger amount, thus decreasing unit production costs. The petrochemical industry is characterised by its high upfront capital investment requirements. In order to lower the unit production cost, the largest possible production scale must be developed.
- **Learning effects** - By having adopted a technology over a longer time, more knowledge and experience is gained, incrementally improving the performance. Conventional technologies used in the petrochemical industry have been in use for a long time. The assets harbouring these technologies have been maintained, and incrementally improved over this time span, creating increasingly efficient production chains inside the petrochemical plants.
- **Adaptive expectations** - The increase in the adoption of a technology reduces the uncertainty of the technology, increasing the confidence in the product and process. Many toxic, explosive and otherwise dangerous substances are used in the petrochemical industry. These circumstances necessitate robust safety protocol in order to create a safe working environment. In addition to the safety concerns, the industry's continuous production processes demand that equipment operates reliably over extended periods, minimizing the risk of unexpected maintenance interruptions.
- **Network effects** - Cumulative adoption of a certain technology creates advantages and added value to the technology. The petrochemical industry is often geographically integrated. This integration creates cluster-scale network economy advantages. The technical integration within these clusters have created an advantage for energy efficiency improvements, enabling further learning effects and economies of scale advantages within the cluster.

Studying the path dependence present in the petrochemical industry is an interesting avenue to gain insight on lock-ins inhibiting the transition to low carbon hydrogen. Understanding the lock-ins present generates valuable insights on how to *break* them, enabling path creation. Additionally, the self-reinforcing mechanisms that lead to the lock-in are different per industry (Onufrey and Bergek, 2015). For this study, it is of importance to explore the mechanisms that influence the petrochemical industry.

3.2.2 Lock-In

Through past events and decisions and self-reinforcing mechanisms, future path trajectories are increasingly constrained, until alternative paths are no longer viable options. This locked-in state, which is the 'end stage' of path dependency, contributes to the hard-to-abate nature of the petrochemical industry.

Lock-in can generally be divided in three phases; the lock-in source, (self)-reinforcing mechanisms, and the final lock-in. The lock-in sources represents the origin from which self-reinforcing mechanisms can be enabled. These are pre-existing factors that create dependencies on particular technologies, policies and systems. These sources are strengthened through (self-)reinforcing mechanisms, ultimately resulting in the final outcome of lock-in.

There is a specific type of lock-in which the petrochemical industry's situation encompasses nicely; *Carbon Lock-in.* Carbon lock-in describes a phenomenon where economic, technological, institutional and behavioural structures reinforce the reliance on carbon-intensive processes and feedstocks (Seto et al., 2016) (Unruh, 2000). The industry's high-energy processes such as steam cracking and catalytic reforming are at the core of the industry. The dual reliance on hydrocarbons both as an energy source and as essential feedstocks for these processes make decarbonisation more complex compared to other sectors. Carbon lock-in can be divided in three categories; Infrastructural and Technological Lock-In, Institutional Lock-In, and Behavioural Lock-in. These lock-in types are explored and applied, respectively, to the petrochemical industry. In section 6, The lock-ins are further explored by investigating the lock-in sources and reinforcing mechanisms present.

- **Infrastructural and Technological Lock-In**

  Infrastructural and technological lock-in occurs when long-lived physical infrastructure and technological investments commit societies to carbon-intensive energy pathways that are difficult or costly to alter. This lock-in type emphasises the importance that initial conditions and early decision-making have on the path trajectory.

  Technology and infrastructure are closely related. Both require substantial capital investment and have long operational lifespans. The adoption of a particular technology is influenced by the existing infrastructure, while the introduction of new technology, in turn, drives the development and expansion of supporting infrastructure. This self-reinforcing process results in their continuous co-evolution.

  Seto et al. describe the economic lifecycle of energy assets, visualised in Figure 8 (2016). During the investment period, the investment costs exceed the operating returns, resulting in a negative asset value. After the investment period is finished and the asset is in operation, the asset generates value. First breaking even the costs made in the investment period, it transitions to the profit period. During this period, the profit generation gradually declines overtime as the asset depreciates. The decision horizon starts when the asset starts decreasing in returns as more operation and maintenance costs start to accumulate. In the decision horizon, a choice must be made regarding a retrofit or replacement of the asset. In this decision-making window, the dominant political, technological, and social landscape is has significant influence on the final decision outcome.

  This asset lifecycle in the petrochemical industry is typically 20 to 30 years long, signifying the importance of this decision making window (Janipour et al., 2020). Early termination of an asset result in stranded profits, or stranded investments. After the replacement line vertically placed in the figure, the potential value generation of different technologies is forecasted. The incumbent technology shows higher value potential because of increasing returns of adoption.

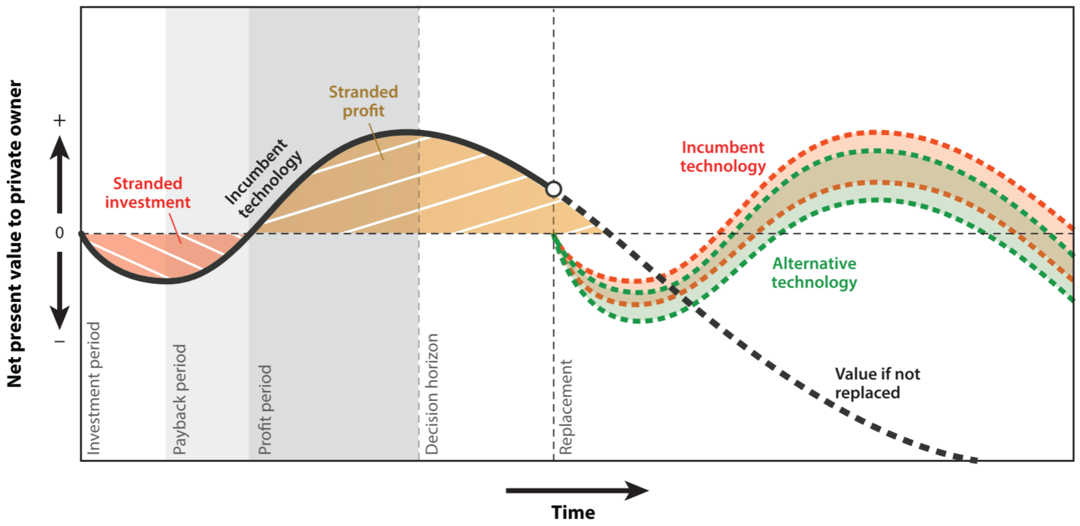


Figure 8: Visualisation of the lifecycle of industry assets and their economic value. During the initial investment, the capital costs exceed the operational costs. After the break-even moment, the asset generates profits until depreciation starts to reduce this value generation. When the value generation starts to reduce, the decision-making horizon starts. This window for replacement of the asset with a conventional technology, or an alternative is heavily influenced by the dominant political, technological and social landscape at that time. (Seto et al., 2016).

Besides the operational assets, the supporting- and energy demanding infrastructure further contribute to carbon lock-in. The high sunk-costs and long lifespan of supporting infrastructure such as pipelines create similar challenges as the industrial plants' assets. Additionally, to better reap the benefits of being located in close proximity to other parties in the value chain, fixed transporting solutions are codeveloped in collaborating organisations. Such collaborations foster interconnections and interdependencies within a cluster, further integrating the system (de Haas and van Dril, 2022). This integration optimises the incumbent processes, creating higher barriers for emerging alternative technologies (Janipour et al., 2020).

A densely integrated system, whilst fostering optimisation gains, inhibits alternative low carbon technologies from being adopted. Adopting these technologies results in suboptimal technology compatibility, reducing the efficiency of the process. Alternative technologies could also be completely incompatible because of existing supporting infrastructure (Janipour et al., 2020).

- **Institutional Lock-In**

  Institutional lock-in reinforces infrastructural and technological lock-in through conscious efforts made by powerful economic, social and political actors. These actors coordinate their efforts to reinforce the favourable status-quo or seek to create a new favourable status-quo in line with their interests. This lock-in source is defined as *Elite Capture* (Goldstein et al., 2023). Actors that either try to conserve the status-quo, or change them, try to do so through institutions. Through these institutions, policies are created. These policies adjust the playing field and path trajectories within the industry.

  In the petrochemical industry, elite capture is seen in the extensive lobbying efforts that influence environmental regulations or delay stricter emission targets (CEO, 2025). By embedding themselves in policymaking institutions, the dominant actors limit the uptake of radical decarbonization technologies, thus maintaining the status-quo.

European Institutions have incentivised energy efficiency improvements in order to lower emission levels. These policies mainly result in incremental improvements on existing assets, in the same window of opportunity in which more radical emission reduction technologies can be implemented. Additionally, the performance gap between the existing technology and alternative, decarbonising technologies further expands when implementing incremental improvements.

The petrochemical industry has strong safety standards, as it harnesses harmful processes and toxic substances. The introduction of new technologies requires updated safety measures, which may in turn create new safety risks within the sector. The organization and implementation of new safety protocols discourage the industry from adopting new technologies (Janipour et al., 2020).

Breaking institutional lock-in to prompt a system-level transition to a decarbonizing trajectory requires efforts to plant, and foster the growth of, seeds of transition, mindfully deviating from the status quo (Jacobsson and Lauber, 2006). Transitions can begin with organic responses to incentives in the status quo economic and political system, for example, encouraging innovations by corporate interests that coincidentally reduce carbon emissions.

- **Behavioral Lock-In**

  In general, climate change is largely caused by human behavioural patterns which are unsustainable (Seto et al., 2016). These behavioural patterns codevelop with industry, establishing habits, routines and preferences. Technologies such as refrigerators and air-conditioning, or synthetic textiles and plastic packaging are ingrained in society. Transitioning away from the use of unsustainable, everyday items poses a significant challenge as social norms and values emerge and are established over a long time span (Goldstein et al., 2023).

  In the petrochemical industry, behavioural lock-in manifests in the persistent use of plastic products and fossil-based chemicals. Despite increasing awareness on the consequences of the consumption of unsustainable products, the transition to more sustainable alternatives is slow. The global reliance on fossil derived products based on affordability, convenience, and ingrained habits are factors that act as barriers to transition (Heidbreder et al., 2019).

Illustrated Lock-in Cycle

A good example showing all the lock-in categories is made by Unruh (2000). In Figure 9, a simplified cycle of the lock-in of an electric power network. When society starts using more electrity, institutional actors regulating the system coordinate the signal of increased of consumption towards increase power generation towards firms. These firms invest in power generation by expanding the necessary assets. The cycle then comes back around to the social response of more energy usage. This can be the result of, for example, diffusion of more energy consuming technologies or behavioural changes because of price reduction as a result of economies of scale. Unruh states that the increasing returns to adoption such as scale- and learning economies, as well as adaptive expectations are a main driving force for this lock-in cycle.

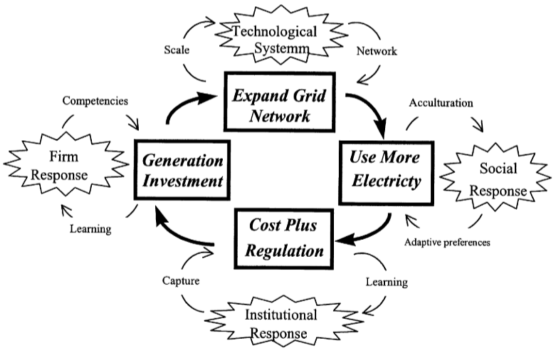


Figure 9: Simplified lock-in cycle of electric power networks (Unruh, 2000).

Lock-In Sources

Lock-in sources are the point of origin which reinforcing mechanisms develop, constraining further decision-making variety and enabling path dependency. In this research, the lock-in sources found by Goldstein for the energy sector (2023) are used together with the lock-in sources found by Janipour for the chemical sector (2020).

Table 1: The lock-in sources present in the chemical sector (Janipour et al., 2020) with an additional column presenting the applicability to the petrochemical sector.

Lock-in Sources	**Description**	**Applicability to the Petrochemical Sector**
Technological incompatibility	Technological incompatibility means a low-carbon technology cannot be implemented with the existing, or another technology.	Implementing CCS subsystems to produce blue hydrogen will make electrification harder to realise.
System integration	Highly integrated systems constrain subsystem replacements because of risking stranded assets which were interconnected with the subsystem.	Fixed transport connections between companies such as pipelines and exchange of waste heat increase the likelihood of stranded assets when implementing new technologies.
Sunk Costs	High capital costs of existing long-lived installations incentivize the continuance of the assets until these are depreciated.	The high up-front capital costs of existing assets with long life spans discourage replacement and motivate energy efficiency upgrades, further increasing the sunk costs.
Policy Inconsistency	Conflict between energy reduction policies and decarbonising policies, leading to short-term energy efficiency investments, increasing the sunk costs.	The Dutch decarbonization goals could counteract energy-saving goals, as low-carbon technologies generally require more energy to operate.
Safety Routines	The industry is associated with many safety risks, resulting in complex and prioritized safety standards. New technologies would require an overhaul of these standards to harness the quality.	Creating new safety standards and routines requires major overhauls. Additionally, the cumulative learning effects that are incorporated in incumbent safety standards need to be matched, requiring substantial effort and time.

Table 2: Lock-In sources described by Goldstein and applied to the petrochemical sector (2023)

Lock-In Sources	**Description**	**Applicability to Petrochemical Sector**
Existing Infrastructure	Existing infrastructure is already established, including physical and financial infrastructures.	The petrochemical sector relies heavily on long-lived infrastructure such as refineries, petrochemical plants, pipelines, and storage facilities. These assets are optimized for fossil fuels and incur high sunk costs, making transitions to alternatives challenging (Janipour et al., 2020).
Formal Institutional Processes	Existing processes are embedded in laws, policies, and bureaucratic processes, along with operational roles.	Regulatory frameworks and trade agreements have traditionally supported fossil fuel-based production, creating high barriers for alternative technologies like green hydrogen .
Established Markets	Customary behaviors, institutional inertia, and existing networks create high entry costs for alternatives.	Established markets for petrochemical products like plastics, fuels, and industrial chemicals depend on fossil fuel feedstocks, creating resistance to shifts that require expensive or uncertain new technologies.
Available Capital	Business-as-usual choices are easier to fund compared to alternatives.	Investment capital flows more readily into conventional fossil-based projects, with limited availability for high-risk, low-carbon innovations like hydrogen-based petrochemicals.
Elite Capture	Decision-making in large firms is controlled by executives prioritizing the status quo.	Executives and shareholders in petrochemical firms often prioritize profitability and continuity of fossil-based operations over uncertain investments in low-carbon technologies.
Bio-physical Changes Over Time	Land use changes have already reshaped environments and are hard to reverse.	Petrochemical plants significantly contribute to soil and water pollution. This pollution leads to long-term environmental degradation. Decontamination is necessary for (re)building assets, and requires significant resources.
Established Consumption Patterns	Established consumer and industry preferences demand existing products.	Global reliance on fossil fuel-derived products reinforces fossil fuel demand in the petrochemical sector, making adoption of alternatives slower.
Specific Historical Events	Past critical events have established patterns that shape outcomes.	Events like the mid-20th century petrochemical boom and the discovery of shale gas entrenched fossil fuel reliance in the sector.
Environmental Values, Preferences, and Mental Models	Values and preferences shape established practices.	Perceptions of fossil feedstocks being more reliable, efficient, and cost-effective continue to dominate, creating resistance to adopting green alternatives in the petrochemical sector.

3.2.3 Path Creation and Development

The concept of path creation is at the heart of this research. Path creation is defined as the *mindful deviation* from the current incumbent structure which represents the status-quo, in attempt to construct a path which leads to a new system (Garud et al., 2010). Path creation has emerged as a complement, as well as a counterpoint to the path dependency theory. The central argument behind the conceptualisation of path creation is the lack of credit towards entrepreneurial activities in the path dependent theory. Stacey argues that path dependency is an outsider's ontology, observing patterns and mechanisms without interacting (1995). In contrast to path dependency, which heavily focuses on historical aspects and contingent events, path creation emphasizes the conscious choices that actors make to create options and make decisions. This creates an insider's view.

The theory of path creation stems from Schumpeter's concept of *Creative Destruction*, which argues that "any system designed to be efficient at a point in time will not be efficient over a point in time." This suggests that entrepreneurial actions over time lead to the development of innovative and more efficient systems that surpass the functions of existing ones, ultimately rendering the old systems obsolete (Schumpeter and Backhaus, 2003). Path creation thus attempts to pinpoint and analyse the key entrepreneurial processes that lead to the successful development of new systems.

The petrochemical industry is pressured to innovate, creating shifts in technology, regulations and markets. For example, the EU ban on single-use plastics together with societal pressures, push plastic producers to steer away from traditional production processes or risk losing market share.

However, entrepreneurs simply deviating from the incumbent system because they believe that there is something different and better out there is insufficient to create a new path. A new structure embedding the ideas and visions, and protecting them from threats is necessary to have a chance of success (Koput, 2003). As a metaphor, one head of cattle straying from the herd will not create a new herd nor find more fertile pastures, but rather lose its way and die of starvation. Four or five heads of cattle have the ability to create a new herd and together shape the vision of where to go, increasing the chance of success, but never guaranteeing it. Entrepreneurship is a complex process, in which contextual aspects as well as many dynamic factors play an important role in the eventual outcome of entrepreneurial actions.

Path creation has the ability to unlock existing lock-ins, creating new paths that deviate from the current status quo. Carbon lock-in, which has been previously described in subsubsection 3.2.2, can be segmented using the theory. Seto et al. states that the most promising way to overcome carbon lock-in is to foster an institutional lock-in of a new, decarbonizing path (Seto et al., 2016). To add on to this statement, Becker argues that self-reinforcing mechanisms can be manipulated for the purpose of path creation (2016). It seems path creation and development heavily rely on actively engaging with the mechanisms that characterise path dependency. This stabilisation, ultimately leading to a locked-in situation, is to be defined as a neutral term; Both positive and negative traits are linked to path dependency, path creation and development (Buschmann and Oels, 2019).

Resource levels

To sustain the path, and develop it, actors must actively engage with self-reinforcing mechanisms. This engagement requires organisational resources. Organizational resources refer to both tangible and intangible assets that an organization owns or manages. These resources hold strategic importance, allowing the organization to develop and execute strategies that enhance its efficiency and effectiveness (Musiolik et al., 2012). Tangible resources include equipment, finance, and human resources, while intangible resources encompass assets like technological know-how, an actor's reputation, and network contacts (Ortt and Kamp, 2022). Organisational resources can be utilised to gain network resources necessary for strategic planning beyond the firm-level (Unruh, 2000). Network resources are created in inter-firm collaborations and alliances, allowing access to resources of the partners, but also the resources which emerge through the interplay of cooperation (accumulated power, trust and stabilisation). Multiple network resource relations create a web of resources. The interactions in this web generate system-level resources. At the focal cluster-level, system resources such as technology reputation, collective expectations, and symbolic capital become essential enabling factors of path creation possibilities (Farla et al., 2012).

Considering the different resource sources explored above, mindful deviation starts at the mobilisation of organisational resources towards further developing inventions, and creating strategic alliances and cooperations. These created partnerships generate network resources, which in turn can be mobilised towards system-level resources, granting the ability of systemic change. In Figure 10 the relationship between the resources is virtually sketched. The increasing size of the resources visualise the addition of power the accumulated resources generate. Table 3 gives a descriptive overview of the different resource types.

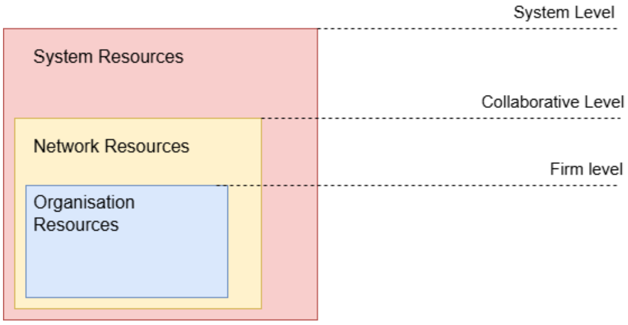


Figure 10: The three levels of resources visually described.

Table 3: Categorization of Organisational, Network, and System Resources (Farla et al., 2012)

Resource Type	**Short Description**	**Examples**
Organisational Resources	Tangible and intangible assets controlled by an organization to support strategies and innovation.	• Financial capital • Technological know-how • Skilled employees • Reputation
Network Resources	Shared resources within networks between multiple organisations, creating collaborative strength in the respective environment.	• Network governance • Member trust • Network reputation • Collaborative platforms
System Resources	Institutional and structural resources generated by sizeable networks collaborating, creating legitimacy and reputational strength.	• Technology Reputation • Industry Standards • Symbolic Capital • Collective Expectations

In the petrochemical sector, the generation of these resources is important. spearheading the system-building activities allows for a leveraged position in the market, potentially gaining a competitive advantage. By creating legitimacy for the desired technological system early, reinforcing mechanisms can be created to gain the upper-hand over alternative technologies, developing a independent path.

3.2.4 Strategy using the Path theories

Gàspàr investigated the applicability of the Path theories by exploring path creation and path dependency as two sides of the same coin (2011). Path dependency is measured in prognostic certainty. In the short term, the prognostic certainty is high, and it is unlikely that the status-quo will change in the time-frame. Path creation is measured using the extent of freedom in decision/-making. When the time-frame grows, so does the power of path creation. More decisions can be made over a longer time-frame, increasing the amount of deviation possible from the status-quo. However, this deviation creates uncertainty, resulting in a greater bandwidth of possible future outlooks. In figure 11 the relationship between the path dependency and creation is visualised.

The time-frame is defined in short, medium and long life-cycles. These cycles are based on technology cycles; short term is interpreted as depletion of stock and life expectancy of the product. Medium term is the life cycle of capital, depreciating over time and thus allowing the assets to be mobilised. Finally, long term is interpreted as multiple life cycles of capital, depreciating and being mobilised. In the chemical industry, these assets are long-lasting, offering only a small window of opportunity when process installations are completely shut down for major overhaul, defined as a turnaround (TAR).

Gàspàr states that *the paradox of strategic development results from opposite movements of the prognostic power of our decisions and of the level of freedom to make decisions in time.* This means short-term projections can easily avoid undesirable changes, but the manoeuvrability of strategic activity is small due to the presence of lock-in. Long-term projections, in comparison, have major manoeuvrability, equipped with the possibility to break the present lock-ins and unlocking paths in the process. However, this process generates uncertainty because it deals with less fixed factors (lock-ins) and more interconnected variables.

An approximation of the solution lies in the medium-term; the prognostic power is strong enough to deal with the level of uncertainty present, projecting the standard deviation of the path over time. Additionally, there is enough freedom in decision making to initiate structural changes, as assets depreciate and resources mobilise in this time frame.

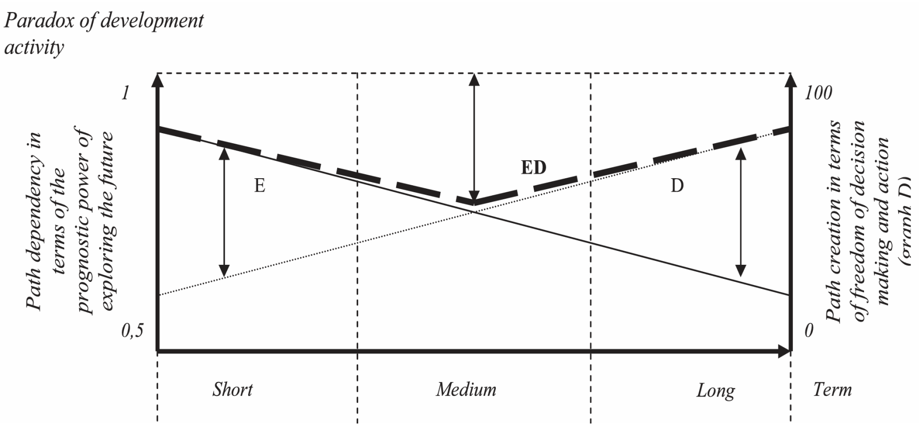


Figure 11: Paradox of strategic development in different timeframes implementing path dependency and path creation (Gáspár, 2011)

3.2.5 Synthesis of the Path

To attempt to understand the processes and outcomes driving technological development, the concepts of path dependence, creation and development must be integrated (Hirsch and Gillespie, 2001). Having explored the basis for path dependency as path creation, with the main properties shown in Table 4, different ways of connecting the two are described in this chapter.

Table 4: The basic properties of the Path Theories (adopted from (Meyer and Schubert, 2007)).

Path Theory	Concept of constitution	Path properties
Path Dependency	Paths emerge behind the back of *actors*, they are not and cannot be controlled by them.	• History Matters • Increasing Returns • Lock-In
Path Creation & Development	Paths can deliberately be created **and** developed by actors, if they are able to generate, and mobilise the necessary resources	• History **and** agency matter • Generating, and mobilising resources • Reinforcing mechanisms as path stabiliser

The theories have been methodically integrated in a sequential manner. In figure 12 the sequence is shown. The time frame is set out against industry maturity. The triangular shapes surrounding the historical path and future paths represent the bandwidth of freedom of choice. Taking the perspective of the present, when the industry was in a nascent stage, the decision-making freedom was large; no self-reinforcing processes had yet to be established. As the path approaches the present, less freedom is observed, showcasing the stabilising lock-in taking place.

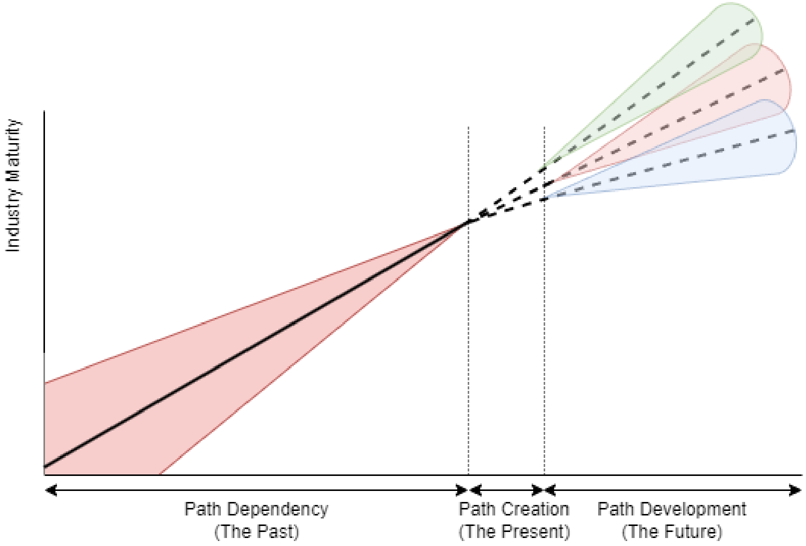


Figure 12: Visualisation of the paths in sequence

In the present, path creation initiatives take place. These initiatives are based on a future vision of what could/should be the industry of the future. As described in subsubsection 3.2.3, a path which completely deviates from the embedded system has no chance of survival if there is no shock present which allows for radical change. Thus, the created paths comply with the existing path, to slowly deviate from it into a different direction. Still maintaining the perspective of the present, the bandwidths of the future paths represent the decreasing prognostic power over time; The more we plan for the future, the greater the uncertainty becomes. Nevertheless, during this period, the flexibility in decision-making increases, permitting more substantial deviations to occur.

Path creation opportunities, besides entrepreneurial initiatives happening at any time, can also be created by shocks. Shocks, similarly described in subsubsection 3.2.1, are unpredictable events which influence a path's trajectory. Shocks threaten to destabilize core structures of a technological system through the disruption of the self-reinforcing mechanisms. For example, the European energy crisis, beginning in 2021, escalated when Russia weaponised energy supplies following the invasion on Ukraine. Russia supplied about 40% of Europe's gas imports, threatening the energy security of European countries. These events led to re-investments in fossil-fuels and coal to ensure energy security (IEA, 2023); Germany and the Netherlands reactivated coal power plants to compensate for the gas shortages, and long-term contracts for liquid natural gas imports were signed to regain control over the energy security. Society also the experienced the impact of radically increased energy prices. All three carbon lock-in types described earlier this chapter were reinforced.

Paradoxically, the crisis also highlights the importance of diversifying the energy sources, expanding the renewable energy infrastructure for long-term security. To counteract the dependency on Russian energy, the REpowerEU plan aims to accelerate wind and solar capacity along with improved energy efficiency (European Commission, 2022). This example neatly shows the trajectory adjustments that are made through decision-making in times of uncertainty and chaos.

3.3 Technology Innovation System

In chapter 1.5, the level of analysis was considered. Because of the nascent stage which the low-carbon hydrogen value chain is in, actors in this value chain need to consider the market dynamics at play. Mainly because of this argument, the meso-level is chosen as level of analysis. However, because this study is focused on the company perspective, a connection must be established between the meso-level and the micro-level. To be able to do this systematically, the Technology Innovation System Framework is adopted.

A Technology Innovation System (TIS) can be defined as *"a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology"* (Carlsson and Stankiewicz, 1991). The four main structures in the system are Technology, Agents, Institutions, and Networks (Bergek et al., 2015). Analysis of these structures and their respective interactions and relations allows for a performance evaluation of the focal TIS. The main four structures are described below.

- **Technology** - The main product or field of knowledge around which the innovation system is built. Technology is the application of scientific knowledge which help in overcoming practical socio-economic challenges.
- **Agents** - The organisations, firms, and individuals that are in some way involved in the development, diffusion and adoption of the technology around which the technological innovation system is built. These agents include knowledge institutions, education organizations, market and industry actors, public and governmental organizations.
- **Institutions** - The formal and informal rules, or codes of conduct present within the innovation system shaping the dynamics and interactions. Formal institutions consist of laws and regulations. Informal institutions describe norms, values, and other ethical codes that guide actors within the system.
- **Networks** - The connections between the agents linked together in the system, providing the interactions that improve the system's performance.

The combination of the system's dynamics and evaluative possibilities that the TIS framework possess is very compatible with this research for multiple reasons. Firstly, the TIS-framework can be applied on a variety of levels of analyses. National, sectoral, and company-leveled TIS analyses have been conducted (Fagerberg, 2011) (Malerba, 2002) (Ortt and Kamp, 2022). Considering the scope of this study, the TIS framework can help identify cluster-specific characteristics and dynamics. These characteristics and dynamics, in turn, complement exploring path creation and development initiated by agents within the system. The second reason is the significant roles that technology, agents, institutions and networks have in the framework. These structures are compatible with the general idea of path creation that 'mindful deviation' cannot be initiated in a perpendicular fashion regarding the status-quo of the industry. The deviation should be coordinated in such a way that carries away from the embedded system of agents, institutions and networks, rather than isolating itself entirely (Garud and Karnøe, 2001). Finally, TIS analysis can highlight the dynamic interactions among the three structural components, pinpointing processes that foster beneficial ecosystems for the flourishing of path creation (Planko et al., 2017).

Taking everything into account, the TIS framework enables a compatible link between the meso-leveled analysis and the micro-level perspective that is explored in this study. By offering a structured approach to examining innovation systems, it facilitates an understanding of how emerging technological and institutional changes interact with existing industry structures. This compatibility allows for an exploration of both the broader systemic forces that shape industrial transformation and the localized, agent-driven dynamics that influence path creation.

3.3.1 System Transition

To break away from the current system that is incompatible with the envisioned future of clean energy, a system transition is necessary. The TIS-framework is increasingly often applied to transitions towards clean energy technology, used to explain differences in system structure, rigidity, and path dependence (Markard et al., 2015). Furthermore, the application to similar topics related to the research at hand further proves the compatibility of the framework with this study (Markard et al., 2020). The differences between systems can lead to potential path creation opportunities. Additionally, it may enable accelerated decline of 'unwanted' technologies, a mechanism closely related to breaking lock-ins.

The path theorem has great functionality in analysing the transition away from an incumbent TIS, to the desired TIS. Path dependency analysis in the industry cluster identify the building blocks that have self-reinforcing processes, leading to lock-ins of the incumbent TIS. Whilst being an inhibitor for path creation, Path dependency is also a desirable phenomenon when developing a created path towards a new TIS. Enabling self-reinforcing processes which drive the path towards the desirable TIS will reduce the external support necessary, improving the independency and stability of the system. Furthermore, the conditions influencing the building blocks give further insight on which paths can be created. In figure 14 the use of the path theorem to enable system transition is visualised.

However, there are multiple TIS configurations possible which can reach the decarbonisation goals set in the Paris Agreement and NDC's. In addition to low-carbon hydrogen, there are other energy carriers and technologies which can help reduce the emissions produced. Inclusion of the TIS belonging to alternative technologies is important to keep in account (Markard et al., 2015). Building blocks may be similar for multiple technology innovation systems. Creating paths for these building blocks would postpone the necessity to dedicate to one system, maintaining flexibility. This flexibility is a valuable asset in transitions under uncertain environments.

3.3.2 TIS - Company Perspective

The TIS framework can be applied to different levels of analysis. Whilst it is mainly used for policy making, attempts to take the company's perspective have been made. A framework has been created for formulating niche introduction strategies when large-scale diffusion is hampered by barriers, approaching the problem from the company's perspective (Ortt and Kamp, 2022). The framework consists of 7 *Building Blocks*, which are influenced by 7 *Influencing Conditions*. These are visualised in figure 13. By first assessing the status of the building blocks, barriers can be identified and niche market introduction strategies can be formulated accordingly. The influencing conditions help identify why some building blocks are incomplete, which is useful for further specifying the introduction strategy with respect to timing, scale, and strategy type.

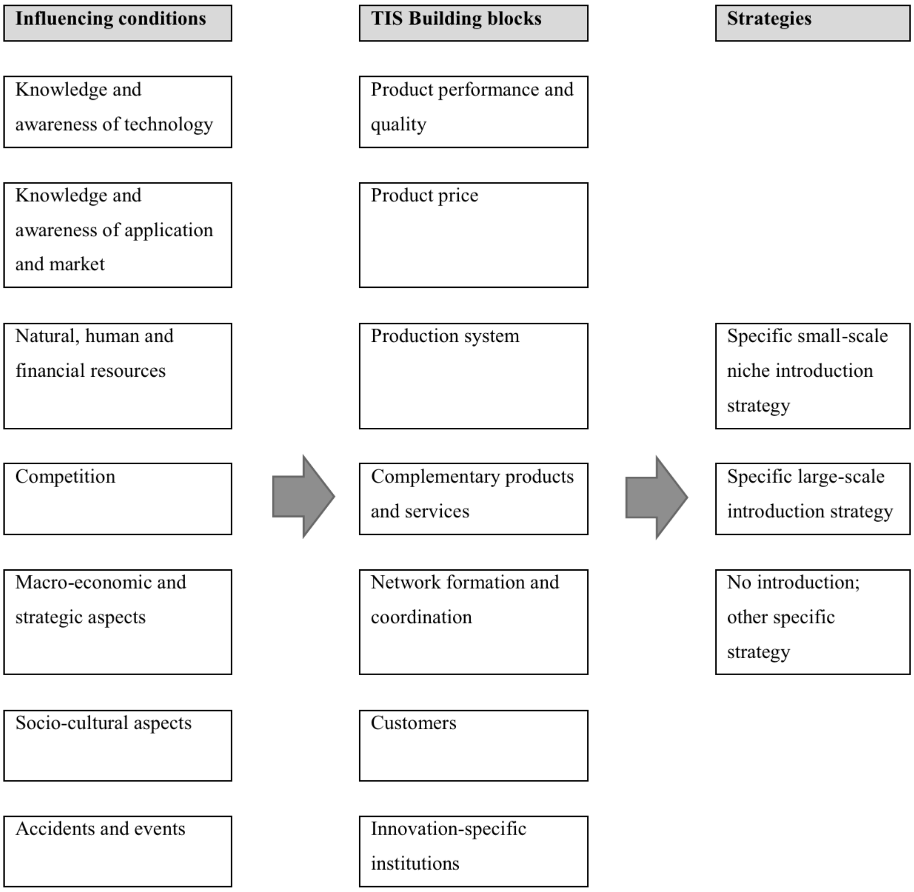


Figure 13: Technology Innovation System Framework from a Company's Perspective (Ortt and Kamp, 2022)

3.4 Synthesis of Technology Innovation Systems Framework and Path Theorem

The energy transition of an industry cluster is a full system transition; The business-to-business nature of the industry has resulted in a interdependency between actors which improves efficiency and enables economies of scale in the status-quo. Additionally, the development of the industry over a long time-span has created systemic barriers, enforced by industry dynamics. Throughout this section, two frameworks have been explored. These frameworks act as the foundation of this research. Individually, each framework captures only a part of the formulated problem:

- **The Path Theorem** excels at describing and creating an in-depth understanding of the dynamics present. Path dependency shows how a system reaches a locked-in state by uncovering self-reinforcing mechanisms, originating from lock-in sources. Path creation and development offers perspective on mindfully deviating from present self-reinforcing mechanisms, and supporting new trajectories. However because the framework offers little empirical diagnostic guidance, few concrete, actionable steps for intervention remain.
- **The Technology Innovation System Framework** excels at the evaluation of the system's performance through concrete building blocks and underlying influencing conditions. Through this evaluation, strong points and weaknesses of the system can be pinpointed. However, the TIS-framework's diagnostic ability is static; it considers only the chosen moment in time in the evaluation. *Why* a certain building block remains consistently strong or weak is not included in-depth.

However, in this research, we attempt to combine the two frameworks to benefit from the best of both worlds in order to research the energy transition. Due to the required moment in time for TIS analysis, two TIS' are analysed; the current TIS, based on oil and gas and the future desired TIS, based on low-carbon hydrogen. The moment in time is an interval; the 'present' state is analysed whilst also looking at the forecast status.

The system transition is defined in this study as the dismantling of the current TIS' building blocks, whilst developing the desired TIS' building blocks. This development may take place through the remobilisation of the dismantled resources, or through new, emerging resources. By implementing path dependency, a better understanding can be generated as to *why* certain building blocks perform well/poorly, uncovering dynamics that entrench the building block's status. The lock-in type, underlying self-reinforcing mechanisms and lock-in sources have significant value, facilitating strategy-formulation.

Path creation can be initiated by targeting either unstable incumbent building blocks, or desired building blocks with development potential. Targeting the prospects of the two systems is in the mindful deviation nature of path creation. Path development then looks to support these deviations by enabling desired self-reinforcing mechanisms, accelerating the dismantling of the current TIS, or the development of the desired TIS.

Synthesis Visualisation

This synthesis is visualised in Figure 14. The current, incumbent technology innovation system is positioned on the left, with its building blocks and influencing conditions below. These are coloured green prematurely to signify the overall strong performance of the system. More in-depth evaluation is done in subsection 5.2.

The red arrow originating from the incumbent TIS represents the historical inertia entrenching the cluster to remain fossil-centric. The horizontal part of the blue arrow represents the mindful deviation in order to branch off of the incumbent path trajectory. After the initial deviation, the blue arrow represents the support of the new path, developing the desired TIS and its building blocks. Finally, the red arrow originating from the desired TIS shows the created self-reinforcing mechanisms of path development creating a new stable path.

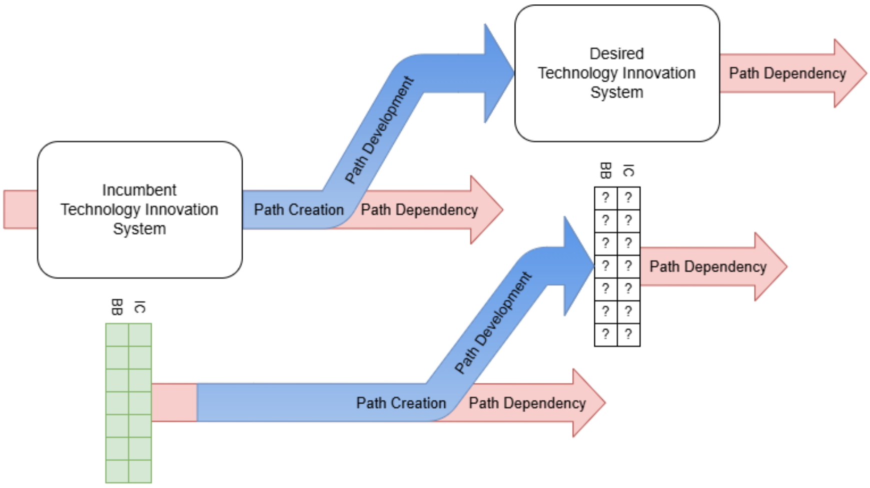


Figure 14: Visual representation of the compatibility between the TIS framework and The Path theorem. *BB* represents the building blocks, and *IC* represents the influencing conditions as proposed by Ortt and Kamp (2022).

3.5 Sub-Questions

Having explored the concepts and theories adopted in this research, the main research question is divided into 4 sub-questions. The main research question is repeated below. In section 4 the methodology on how these questions will be approached is further explained.

"How can a company organise for path creation, and drive its development in the petrochemical industry under a transitioning environment towards low carbon hydrogen?"

1. *What is the status of the incumbent, and desired Technology Innovation System?* To be able to apply the synthesis made of the two foundation frameworks defined in subsection 3.4, the two Technology Innovation Systems must be analysed individually. The analysis consists of exploring the respective building blocks, evaluating their current performance. An outlook on the future status of these building blocks is forecast through exploring the present influencing conditions. Through the combination of the building blocks and influencing conditions, the stability of the Technology Innovation Systems is gauged.

   Deliverable: An evaluation of the status of the existing, and desired Technology Innovation System.

2. *What are the industry dynamics, and self-reinforcing mechanisms specifically, influencing the path trajectory of a TIS transition in the petrochemical industry?*

   The path dependency theory is explored by describing the industry dynamics present in the cluster. These industry dynamics may inhibit the development of desired building blocks, or uncover potential drivers for accelerated development. The industry dynamics are examined through identifying underlying self-reinforcing mechanisms. A thorough understanding of the self-reinforcing mechanisms identify points of leverage, key for initiating path creation.

   Deliverable: Description of the industry dynamics, and self-reinforcing mechanisms specifically, present in the focal petrochemical sector.

3. *How to create, and develop a new path in a system transition context?*

   The objective of this sub-question is to specify points of leverage for deviation of the current path trajectory, towards a path developing the desired Technological Innovation System. Path creation and development are synthesised in succession to path dependency. The points of leverage are extracted from self-reinforcing mechanisms. The potential of the created path is described through building blocks and influencing conditions, using resource-levels to more accurately identify the needs of the initiatives.

   Deliverable: Proposals of mindful deviations towards the development of the desired Technology Innovation System.

4 Methodology

The methodology chapter outlines the research design, data collection methods and analysis techniques used in the study. First an overview of the general research approach is described, after which the research methods are detailed per sub-question. The methodology is concluded with a research flow diagram, visualised in Figure 15.

4.1 General Research Approach

This research will use a exploratory, qualitative research approach with a case study design to explore the industry dynamics, specifically the self-reinforcing mechanisms that influence path creation in a system transition context. A case is selected, and analysed through the use of literature research and semi-structured interviews. The research design is guided by iterative learning; early insights are fed back into data collection rounds, allowing for exploratory concepts to be refined as the study progresses. This assists in validating the study's research. An overview of the data collection and analysis methods are shown in Table 5.

Table 5: Overview of sub-questions, deliverables, methods of data collection and analysis

Sub-question	**Key deliverable**	**Data-collection method(s)**	**Data-analysis method(s)**
TIS Evaluation	Status evaluation of Current TIS and Desired TIS	Literature Research based on grey (and academic) literature	TIS-Framework (Ortt and Kamp, 2022)
Path Dependency	Description of present industry dynamics	Semi-structured interviews	Interview summaries with thematic coding
Path Creation	Path Creation proposals	Semi-structured interviews Literature Research	Interview summaries with thematic coding

4.2 Data Collection Methods

The data collection methods applied in the remaining chapters is divided into three primary methods: (1) Case selection, (2) Literature research and (3) Semi-structured interviews. The data collection methods are described individually, and then coupled to the sub-questions in subsubsection 4.2.4.

4.2.1 Case Selection

Case selection is applied to enhance the exploration of the company perspective desired in this research and bridges the gap between theoretical findings and practical application. A case study approach allows for a more focused, and in-depth examination of the specific dynamics present influencing the energy transition. The case study is based on the petrochemical cluster present in the Port's industrial complex, and has been contextually introduced in section 1. This meso-level scope incorporates the cluster's interdependencies, which is the main reason for selecting a system-based approach in this research. The case study sketches the playing field, in which the methods of analyses are applied.

Furthermore, the case study method is well-compatible with the Technology Innovation Framework, described in subsubsection 3.3.2. The TIS-framework enhances the case by its systematic approach. The structural scoping of the case is done through the TIS-analyses in section 5. The scoping methodology of Bergek is applied, selecting a focusing device, the breadth and depth and the spatial domain of the respective Technology Innovation Systems (2015). With the aggregated case built around the energy transition to hydrogen in PoR's petrochemical cluster, a more practical implementation of the theoretical frameworks acting as the foundation of this study is achieved.

4.2.2 Literature research

Literature research is applied to understand the status of the current, and desired TIS. The analysis of the building blocks and influencing conditions are based on mostly grey literature. It is assumed that grey literature consists more recent contents, and that it is written with a company approach in mind. Examples of grey literature incorporated are: Industry-related news outlets (Industrielinqs, Reuters), policy documents (European Commission, Rijksoverheid), research reports (PBL, ICIS) and roadmaps (PoR, DeltaLinqs, TKI).

4.2.3 Semi-structured interviews

Semi-structured interviews with actors within the research' case study enables a in-depth look at the industry's dynamics and attitude towards the energy-transition. Using the TIS analysis, targeted questions are asked concerning what building blocks are most lacking, and which have the most potential for development. These interviews generate a nuanced market-insight of the energy transition within the focal petrochemical cluster. Furthermore, the interviews can indirectly validate the TIS evaluations, and enable the discussion of concept self-reinforcing mechanisms and path creation.

Interview Themes

The semi-structured nature of the interviews is represented through the use of themes. The interview themes are linked to the sub-questions, which have been formulated in subsection 3.5. The purpose of the interviews is to enable the iterative learning process by discussing case-applied literature findings and validating them. The guiding inquiry sequence per theme is found in subsubsection A.3.1. The interview themes are linked to the sub-questions below.

- The first theme explored through the interviews is *path dependency*, allowing the participant to voice their expert opinion and experience on industry dynamics and events that influence the development of energy-transition related projects. This theme is guided through open-ended questions, without the use of the TIS structure. More directed questions related to lock-ins, and lock-in sources are asked if these don't naturally originate from the dialogue.
- The second theme explored through the interviews is *path creation and development*. In this theme, the participant is asked to voice their expert opinion on how deliberate choices changing or diversifying the industry's activities should be made. The company's role in this is also discussed. More directed questions related to organisational capabilities, and collaboration are asked if these don't naturally originate from the dialogue.
- The third theme explored through the interviews is the TIS-framework, concept self-reinforcing mechanisms and concept path creation proposals. The dialogue prior to opening this theme is structured in the this theme. By showing and explaining the TIS' building blocks, the prior themes are discussed in a more structured line of inquiry. An evaluation of the desired building blocks is requested. The most critical building blocks are then pinpointed, after which is potential self-reinforcing mechanisms are discussed.

  To conclude, the participant is asked what he/she thinks is the most essential building block to develop. Consequentially, concept path creation propositions are then discussed. Through the discussions present in this discussion, the iterative nature of the research methodology is enabled.

Participant selection

For this research, a broad participant selection pool is desired to align with the exploratory nature of this research. Commercial producers, trade associations, cluster governance authorities and industry service providers are of interest for this study. These organisation types are compatible with several building blocks of the TIS-frameworks; Trade association has expertise on the *market formation and coordination* building block, cluster governance authorities have insight on the *market formation and coordination* and *innovation-specific institutions* building blocks, whilst commercial producers have a more bottom-up perspective on the *market formation and coordination*, *customers* and *innovation-specific institutions* building blocks for example.

The participants are selected through active communication efforts with Port of Rotterdam. The themes, with a concise description of the context is discussed with the point of contact, after which potential participants are invited. The participants selection process is also discussed with the PoR point of contact, but there are initial roles and backgrounds which ensure valuable insights from the interviews.

For example, industry veterans have experienced the industry dynamics described in theme 1, and possess valuable insight on how the industry reacts. Deliberate forces of change can also be identified by industry veterans. Strategy advisors also have this insight, and also posses valuable insight on what companies are trying to achieve, and what their attitude is in the short- and long term.

For the interviews, 4-7 participants are desirable. With this number of participants, the study has responses that will saturate the explorative purpose of the three themes, and also allow for triangulation of the TIS-analyses. In Table 6, an overview of the participants and their role within the organisation type is given.

Due to the interaction and data collection with human participants, it is important to acquire ethical approval of each participant. Ethical approval is obtained through informed consent, ensuring informed participant anonymity and secure data storage. The ethical considerations are evaluated by TUDelft human research ethics board, and are expanded upon in subsubsection A.3.2

Table 6: Overview of interview participants

Code	Organisation type	Interviewee's role
P1	Complementary service and construction firm	Project Manager
P2	Trade Association	Sustainability Project Leader
P3	State-Owned Enterprise	Strategic Advisor
P4	Commercial Producer	Stakeholder Manager
P5	Commercial Producer	Business Developer

Global interview process

The interview goals, and how these goals will be reached have now been described. However, the interview process includes more subtle steps. For example, introductory opening stating the goal of the interview, and why the particular participant was invited together with participant aftercare are important steps which should not be missed. This process is visualised in subsection A.7.

4.2.4 Methods per sub question

The three sub-questions formulated in subsection 3.5 are all analysed within the selected case. However, the respective frameworks forming the base of this research benefit from the interviews and literature research differently. The TIS-analyses (SQ1) are a more structured type of analysis, exploring seven predefined building blocks and their influencing conditions. The path theorem (SQ2-3) enjoy a more dynamic, abstract approach. Below, the data collection methods per sub-question are described.

Sub-Question 1: TIS-Analysis

The analysis of the two Technology Innovation Systems excel at systematically evaluating the performance through building blocks and influencing conditions. To use the framework in practice, Ortt and Kamp state that each building block requires information gathering using various sources (Ortt and Kamp, 2022). To achieve this triangulation, various literature sources are applied which carry the same narrative.

For the TIS-analyses, literature research will be the main collection method applied to answer the related sub-question. The semi-structured interviews do play an important part in the iterative learning process of the research. As the respective TIS-analyses are built up, the interviews run in a later, parallel fashion. Starting off, a first iteration of the TIS-analyses is made, which assist in guiding the interviews through its semi-structured nature. These interviews generate a nuanced company perspective on the macro scale of the challenge, the cluster-scale, but also what the company/participant's attitude is towards the transition. This generates an insightful, but also more nuanced company perspective, from which a type of weighting factor can be extracted. The weighting factors are reintegrated into the TIS analysis for a second cycle, resulting in a case-specific, more balanced portrayal of the system.

Sub-Question 2: Path Dependency Dynamics

As described in the methods of sub-question 1, the first iteration of the TIS-analysis guide the interviews. The TIS-framework excels at diagnostic power, but lacks the ability to describe dynamics due to the framework's systematic nature. Semi-structured interviews are conducted to characterise the focal cluster and uncover the systemic barriers that entrench the status quo and inhibit the transition to the emerging system.

The iterative learning process is applied in this sub-question too. The iterative process between TIS and interviews not only strengthens the TIS-analyses, but also enhances the interviews; more in-depth dialogue on *why* a certain building block perform well or poorly uncovers path dependency dynamics, translated to the TIS-framework. These dynamics can then be validated in interviews, again highlighting the iterative learning.

Sub-Question 3: Path Creation and Development

Sub-question 3 possesses similar methods of collection to sub-question 2. The iterative learning between the TIS-analysis and path dependency dynamics can also be applied to the path creation and development part of the path theory. The literature research of TIS is used as a starting point for finding points of leverage for path creation. The interviews assist with a complementary company-oriented view, investigating how the participant would organise for energy-transition initiatives. After having generated path creation propositions, these are validated and reflected upon through the interviews. Additionally, existing strategy statements found through literature research are compared to the path creation propositions, for additional reflection of the path.

4.3 Data Analysis

In this section, the analysis methods used on the collected data are described. The case study acts as the platform on which the literature research and semi-structured interviews will be applied. The methods of analysis will be categorised per data collection method.

4.3.1 Literature Research

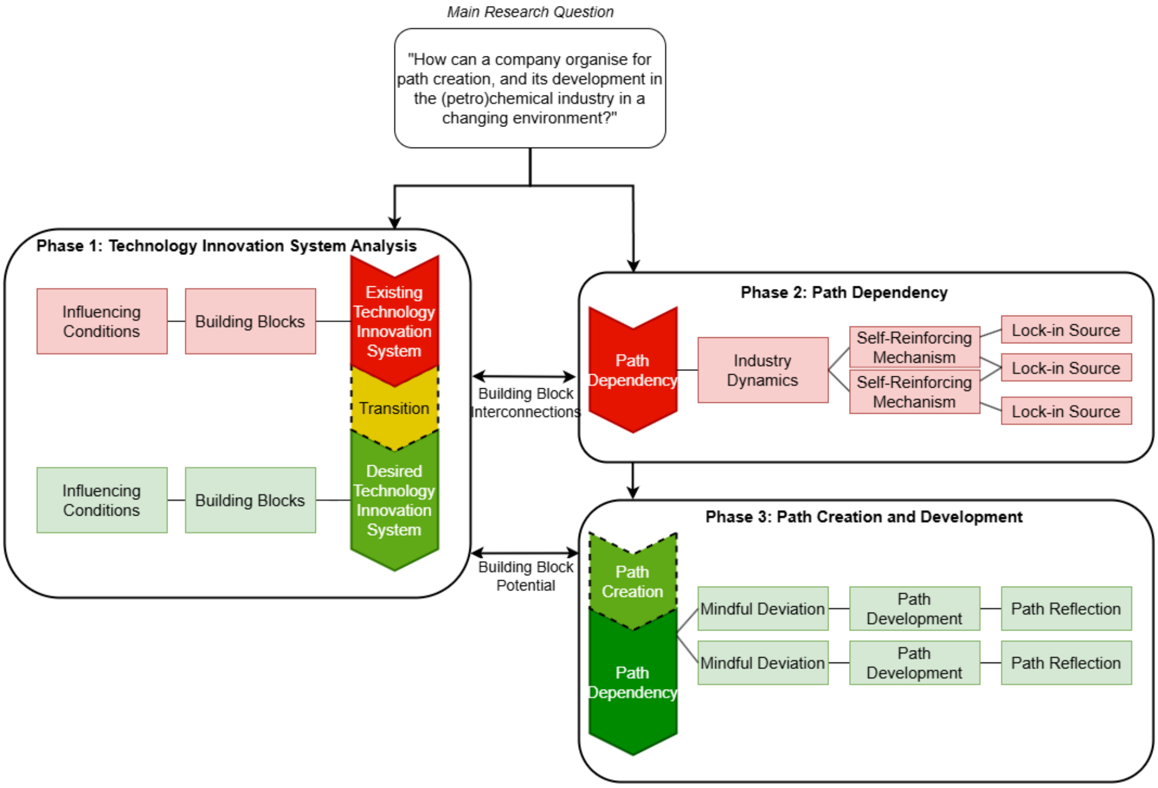
As described earlier, the literature research its main objective is for the evaluation of the TIS. The TIS-framework focused on the company perspective, designed by Ortt and Kamp is the analysis method used for the analysis of the acquired data (2022). This analysis consists of the analysis of seven building blocks, after which the seven influencing conditions are explored to evaluate the stability and resulting dismantlement/development of every building block. In section 5, the analysis process is further explained. The building blocks and influencing conditions are defined and described in subsection A.4.

4.3.2 Semi-Structured Interviews

The semi-structured interviews are analysed through the processing of the transcriptions to a interview summary. This interview summary maintains the same themes established in subsubsection 4.2.3. Due to the semi-structured nature, and not all participants having equal insights on all themes, the data between the themes may not be distributed equally. The analysed data is incorporated throughout the following chapters using a citation-kind of method. (P1) to (P5) are used to argue for statements made.

4.4 Research Flow

In this section the research steps are visualised. Figure 15 shows the links between the different phases. The first three sub-questions are parallel streams of research, all feeding into the framework used for sub-question three. The arrows from the three parallel questions into the framework consist the interview-validated findings. The coloured blocks themselves represent the literature review prior to the interviews. Similar to this, the case selection (sub-question three) is the analysis of the real-world application, with the evaluation arrow the validating interviews.



Phase	*Sub Research Question*	*Outcomes/Deliverables*
Technology Innovation System Analysis	"What is the status of the incumbent, and desired Technology Innovation System?"	• Evaluation of the status of the existing, and desired Technology Innovation System.
Path Dependency	"What are the industry dynamics, and self-reinforcing mechanisms specifically, influencing the path trajectory of a TIS transition in the petrochemical industry?"	• Description of the industry dynamics, and self-reinforcing mechanisms specifically, present in the focal petrochemical sector.
Path Creation and Development	"How to create, and develop a new path in a system transition context?"	• Proposals of mindful deviations towards the development of the desired Technology Innovation System.

Figure 15: Global methodology visualised per phase, connecting the sub-questions and deliverables

5 Technology Innovation System Analysis

5.1 Introduction

To describe the transition, from the incumbent system to a low-carbon hydrogen system, both systems are evaluated using the TIS-framework. Figure 16 points out what components are analysed in the next two chapters. The red square encompasses the incumbent TIS, explored in subsection 5.2. The green square then refers to the desired TIS, explored in subsection 5.3.

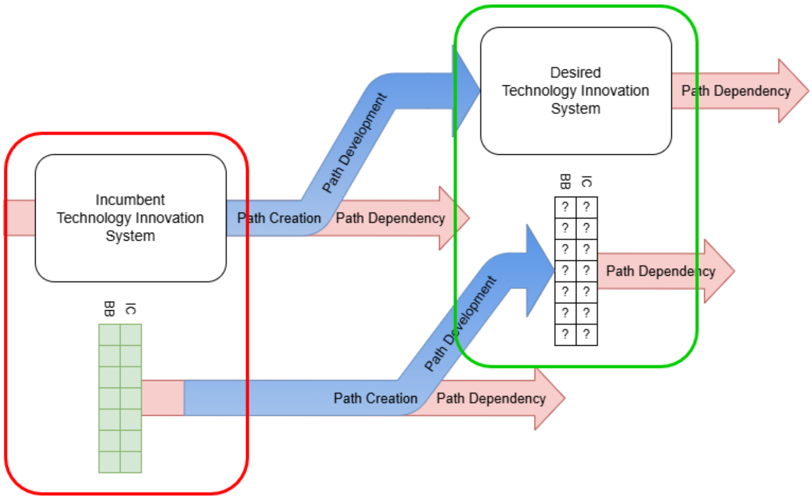


Figure 16: The components focused on in this section. The red square refers to the existing technology innovation system. The green square refers to the desired technology innovation system.

First each TIS scope is determined through three categories. Then, the building blocks are evaluated using data from literature and the semi-structured interviews. To conclude, a global evaluation of both systems are given. The question to be answered in this chapter is:

"What is the current, and forecast performance of the existing, and desired Technology Innovation System?"

5.2 Technology Innovation System - Oil and Gas

To operationalise the incumbent TIS focused on in this research, step 1 of the scheme of analysis created by Bergek (2008) is adopted. This step consists of three choices that assist in the specification and scope of the unit of analysis; the focusing device, breadth and depth, and spatial domain. Below, the choices are made and argued for.

Focusing Device

The first choice to make when specifying the unit of analysis is whether the research is based on a product / artefact or a comprehensive field of knowledge. In this study, both the status-quo, and the desired TIS is analysed to explore the enabling of a system transition. The focusing device compatible to the status-quo, would be *oil and gas*. Oil and gas are both traditionally used feedstocks in the industry. Oil is cracked and refined into fuel types (gasoline, kerosene), to then utilise waste streams for the production of base chemicals such as ethane, propane and butane. Additionally, natural gas is the most used fuel for industrial heat generation. This combination of feedstock and heat generative purposes covers the scoped research focus.

Breadth and Depth

The breadth and depth of the technology innovation system refers to the range of applications and the level of aggregation that the product group includes. The application of interest lies in the feedstock and industrial heat generation purposes. This range is also chosen for the desired TIS to enhance the comparability and the potential resource transferability between the two systems.

In this research, the global status per building block is sufficient in detail. The purpose of the building blocks is to explore the strength of the total system, and identify the points of 'weakness' which might prove to be a good starting point for path creating attempts. This evaluation is done for the moment at which this thesis is written. To gain a better insight on the stability of the building block, a global forecast on how the building blocks may change in the future is done, using the influencing conditions to do so. Weaker building blocks are also further analysed using the influencing condition to reach a level of detail which allows for more insight, useful for said path creating purposes towards the desired TIS.

Spatial Domain

The spatial domain refers to the geographical boundaries in which the TIS operates. This research is limited to the geographical boundaries of the Port of Rotterdam, focusing on the petrochemical industry situated in this geographical cluster. All factors that influence the TIS from outside this scope are considered as external. These external factors are fixed, and are not directly taken into consideration in this research as potential points of adjustment.

5.2.1 Exploration of the Existing Building Blocks

Having scoped the TIS, the seven building blocks can be explored and evaluated. Each building block is introduced shortly, describing what is taken into account per component. At the end of every exploration, the performance of the component is evaluated. If the status of the building block is regarded as poor, the causation is further explored by looking at the seven influencing conditions. These conditions are described in subsection A.4. Below in, the building blocks and performance evaluation is summarised.

Table 7: TIS analysis of oil and gas building blocks with associated influencing conditions.

Building Block	**Evaluated performance**	**Influencing Conditions**
Product performance & quality	Good	**Socio-cultural aspects**: Dutch public awareness of climate impact is rising, eroding the social acceptance of petro-products. **Knowledge and Awareness of Technology**: Century-long optimisation means deep tacit know-how in refiners and users.
Product price	Poor	**Competition & Macro-economic and strategic aspects**: Modern Chinese refineries overflood EU market with cheap products, Dutch operational costs (energy+carbon) too high to compete. **Accidents/events**: Geopolitical shocks create uncertainty and increase price volatility.
Production system	Mediocre	**Macro-economic and strategic aspects**: EU import reliance weakens autonomy in geopolitically volatile times; long-term Norway contracts partly offset risk. **Socio-cultural aspects and Accidents and events**: Induced earthquakes traumatising citizens forced Groningen gas field shutdown, further weakening autonomy.
Complementary products & services	Mixed	**Macro-economic and strategic aspects**: Vast crude tanks (4.5 Mm3) and dense pipeline grid give security of supply; new investments are being reallocated to complementing emerging technology. **Accidents and Events**: War turns Druzhba pipeline into a geopolitical risk node, destabilising distribution. **Competition & Macro-economic and strategic aspects**: Ageing refineries & crackers outcompeted by state-financed refineries in China.
Network formation & coordination	Mediocre	**Resources & Knowledge and awareness of application and market**: Deep physical integration and knowledge hubs create great potential for collaborations. **Macro-economic and strategic aspects & Competition**: Multinational head-office strategies and competition laws keep firms solitary; social capital of the cluster remains thin.
Customers	Good	**Competition**: Low-cost Chinese supply threatens EU share in bulk petrochemicals. **Macro-economic and strategic aspects**: EU fuel-demand decline through electrification & SAF blending mandates reshapes product portfolio. **Knowledge and awareness of application and market**: Global petrochemical growth still pulls demand, softening regional drop.
Innovation-specific institutions	Poor	**Socio-cultural aspects**: Public/political sentiment pivots policy from fossil subsidies to net-zero support. **Macro-economic and strategic aspects & Competition**: EU-ETS + NL carbon tax raise compliance cost; Carbon Border Adjustment not yet protective, squeezing incumbents.

Product performance and quality

The first building block refers to the performance and quality of the product, compared to competing products. This comparison looks at the present, and the near future.

The long timespan in which oil and gas have been used in the industry has allowed for extensive performance and quality improvements. This long development time has resulted in oil and gas being a reliable and well-understood product. Oil and gas knows no viable competition or alternative that encompass the same applicability, though emerging and partial substitutes have been developing, such as bio-based feedstocks, electrification of industrial heat generation and biofuels (IATA, 2024) (Bedocchi and Cassetti, 2025). These emerging substitutes might become serious competitors in the medium to long term due to regulatory measures. Their inherent characteristics are not sufficient to compete with the characteristics of oil and gas.

However, in the future, this building block might become less stable. In the Netherlands, the public awareness regarding climate change, and their personal contribution to resisting this change is increasing; in 2020, 60% of the Dutch population is convinced that their own behaviour have influence on climate change (Kloosterman et al., 2021). This increasing awareness may lead renouncing petrochemical based products, creating a demand for sustainable alternatives.

Due to the lack of competition and alternatives and the well-understood characteristics of the existing oil and gas products and processes, the building block is evaluated as *good*. However, due to the influencing condition *social cultural aspects*, this building block might destabilise over time.

Product Price

The second building block refers to the price of oil and gas for feedstock and industrial heat generation purposes. With similar reasoning to the first building block, oil and gas are relatively cheap compared to emerging substitutes, generating no natural competitive market between the alternatives and the incumbent (P1)(P3)(P4).

However, the energy prices and energy tariffs in the Netherlands are higher than surrounding countries due to the ambitious policies of the Dutch government (van der Chijs, 2025). These high prices result in a competitive disadvantage, damaging the cluster's profits. Looking at global markets, the new Chinese petrochemical production capacity has very low operational costs compared to European refineries, operating older production facilities (Beacham and de Berry, 2024). Competing on product price has thus become increasingly difficult. China is flooding the market with cheap produce, and with the Carbon Border Adjustment Mechanism not yet active, the playing field is uneven for European industry (Narayan and Lee, 2024).

According to van den Beukel et al., the future product price is likely to be characterised by high volatility and an increase in price (2023). Multiple factors for this are mentioned, of which three are given. Firstly, due to Europe's dependency on the international supply chain, oil and gas is an excellent means of exerting political pressure in times of geopolitical conflict. Secondly, the likelihood of OPEC gaining global market share, combined with their unreliable attitude can result in increased price volatility and product dependency. Lastly, the relatively small number of investments by multinational oil companies will reduce oil and gas related exploration and production, resulting in a decrease in market supply, increasing the market price.

The product price building block is currently evaluated as *poor*. Whilst the emerging substitutes are not close to competitive price points, the cluster's competitive position in the traditional markets is severely impoverished. Due to influencing conditions such as the ongoing geopolitical conflicts, Europe's dependency on the international oil and gas supply chain, and investment decrease by multinationals, product prices will likely increase and become increasingly volatile. The influencing conditions *Competition*, *Macro-economic and Strategic Aspects* and *Accidents and Events* play a significant role in the future oil and gas product price, currently forecasting further uncertainty.

Production System

The production system building block evaluates the capability to produce large quantities of high quality products. The production system of oil and gas, also known as the upstream sector, includes the search, drilling, and extraction of oil- and gas fields.

The upstream sector is a core market for many petrochemical companies (P4). Since the oil and gas upstream sector has been established for a long time, its processes have become highly refined, enabling more precise exploration, drilling, and increasingly efficient hydrocarbon extraction over time.

In the European Union, no significant amount of oil and gas is extracted relative to the consumption. The lack of autonomous production results in significant risks as oil and gas, and energy in general, have become a significantly valuable strategic resource. With the largest Dutch natural gas field located in Groningen closing in 2024 due to earthquakes and resulting mental trauma of inhabitants, the national autonomy is also at risk (van den Beukel and van Geuns, 2023) (Eerste Kamer, 2024).

There are some risk mitigation plans active, protecting the autonomy. The long-term contracts with Norway, delivering a steady supply of NG to the Netherlands negates the risk for the foreseeable future. Policies accelerating the extraction of small oil and gas fields in the North Sea will also decrease the dependency.

The absence of domestic production systems creates a significant vulnerable position for the European Union and the Netherlands. The active long-term contracts with Norway for natural gas, and policies encouraging the extraction from fields in the North sea mitigate the risks somewhat. The production system building block is evaluated with *mediocre*.

Conditions influencing the status of the building block consist of *Macro-economic and strategic aspects*, *socio-cultural aspects* and *accidents and events*. The earthquakes in Groningen, causing the closure of the gas fields is a combination of *the socio-cultural aspects* and *accidents and events* influencing conditions. The risk towards autonomy is caused through all three influencing conditions.

Complementary products and services

The building block *complementary products and services* refer to the availability of actors providing additional products and service compatible with the oil and gas product, increasing the value of the product. Due to the amount of factors playing a role in this TIS' building block, only distribution, storage, and utilisation systems are evaluated.

Distribution systems

The distribution systems of oil and gas are well established both nationally as internationally; oil and gas pipelines are established through the whole of Europe, with the Druzhba-pipeline being the longest pipeline in the world. The Druzhba-pipeline's length is 5500 km, originating in West-Russia and runs to West-Germany (IAOT, 2015). Many bypasses off the Druzhba-pipeline exist, creating a vast international distributive network. See Figure 17.

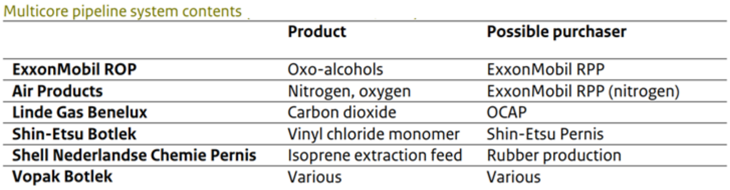
Within the Netherlands, the distribution network for oil and gas are also well-developed, seen in Figure 18. An extensive pipeline network from Groningen throughout the country was developed to distribute the significant amount of extracted natural gas. In addition to the natural gas network, the Port of Rotterdam serves as Europe's primary crude oil hub, handling approximately 100 million tons of crude oil imports (Port of Rotterdam, 2025c). Around half of this volume is processed directly in the port's refineries, while the other half is transported to industrial clusters in neighbouring countries (Samadi et al., 2016)(Port of Rotterdam, 2025c). The distribution of crude oil is done through the a network of pipelines connecting the hub of PoR to other industry clusters, visualised in Figure 18. This network also includes dedicated pipelines, such as those that continuously transport kerosene to both civilian and military airports.

Figure 17: The European Pipeline Network

Figure 18: Overview of the pipeline systems in Rotterdam, connecting adjacent countries to the industry hub (Port of Rotterdam, 2024a)

Besides these nationally owned distribution networks, there are also privately owned distribution networks between companies transporting products and other output streams towards fixed customers. The Multicore pipeline system, visualised in Figure 19, owned by Vopak and the Port of Rotterdam, is one of these systems.

Multicore pipeline system present in Botlek and Pernis,



Multicore pipeline system contents

	Product	Possible purchaser
ExxonMobil ROP	Oxo-alcohols	ExxonMobil RPP
Air Products	Nitrogen, oxygen	ExxonMobil RPP (nitrogen)
Linde Gas Benelux	Carbon dioxide	OCAP
Shin-Etsu Botlek	Vinyl chloride monomer	Shin-Etsu Pernis
Shell Nederlandse Chemie Pernis	Isoprene extraction feed	Rubber production
Vopak Botlek	Various	Various

Figure 19: The multicore pipeline system, with contents and possible purchasers (adopted from (de Haas and van Dril, 2022).

Investments made in the gas distribution systems are majorly aimed at repurposing of pipelines to transport hydrogen (Gasunie, 2024). Whilst these investments consider the critical energy security role that NG distribution has, it does signal future investments to solely consider the energy transition goals.

The distribution systems for oil and gas are both internationally and locally well-established. The distribution systems are evaluated as *good*. The current war between Russia and Ukraine causes the Druzhba-pipeline to become a geopolitical asset. These *Events* and *Macro-Economic and Strategic Aspects* create uncertainty around the reliability of the network, destabilising the building block. The repurposing of existing NG-distribution systems will slowly substitute NG for a renewable energy carrier such as hydrogen, slowly dismantling the building block.

Storage Systems

With the Port of Rotterdam being the largest import port for crude oil and NG, the storage systems are of a similar scale. The Maasvlakte Oil Terminal (MOT) is the largest storage terminal in North-West Europe, with a storage capacity of 4.5 million m3 (MOT, 2025). This is enough volume to reach the 90-day strategy stock obligation, enabling energy security (IEA, 2024).

The oil storage systems are contracting however. In 2021, Vopak announced the repurposing of parts of the Rotterdam oil terminal to store waste-based feedstocks. New investments done in storage systems are focused on emerging, renewable products and feedstocks. Vopak has constructed 16 new storage tanks in PoR dedicated to feedstocks for biodiesel and SAF (Vopak, 2023).

The natural gas storage system is essential to fulfil the Dutch winter demand. Additionally, it acts buffers the fluctuating demand throughout the day. The Netherlands has close to half of its annual consumption (13 billion cubic meters) in gas storage capacity (Hoevers, 2025). The forecast role of natural gas becomes smaller, as renewable energy is scaled up and energy efficiency improvements are made. However, the introduction of renewable energy also introduces more intermittency in the energy grid, resulting in a smaller, but more important role for natural gas to ensure reliability and stability.

Overall, the storage systems for oil and gas are evaluated as *good*. There is plenty of storage, even with the repurposing of oil storage facilities towards renewable products. The storage facilities will remain an important element of the system due to *geopolitical events* pressuring energy reliability. as the role of natural gas in the energy mix becomes smaller, its *strategic aspect* role as buffer and compensator for the intermittent nature of renewable alternatives becomes larger.

Utilisation Systems

Utilisation systems include assets through which oil and gas are applied in the petrochemical processes. Utilisation systems such as fuel refineries, and petrochemical production facilities are considered.

The refineries in Rotterdam possess a large share of the refining power of Europe. Shell Pernis is Europe's largest integrated refinery, capable of refining 404,000 barrels a day (Shell, 2025). Also, the flexibility in terms of products is significant; in 2020, 85% of the total products were fueltypes such as diesel, gasoline LPG and gas oil. The other 15% consisted of petrochemicals, such as naphtha, base oils and bitumen (Oliveira and Schure, 2020).

However, the refineries are under increasing global market pressure. Global mobility electrification reduces demand for fuels, pushing the oil market to shift towards petrochemical production, decreasing demand (International Energy Agency, 2018). European crackers have the highest average age of 45 years. China's average is 11 years in comparison (ICIS, 2024).

Whilst the utilisation systems are well-established, the shifting demand from fuel refining to petrochemicals hurt the existing configuration. The utilisation system is evaluated as *poor*. The *macro-economic aspects* of global overcapacity of petrochemicals combined with the relatively old production plants in Europe result in a large *competitive* disadvantage of the focal petrochemical sector. Production stoppages and production facility closures have already been initiated, with more closures to come.

Network formation and coordination

In the building block network formation and coordination, the interaction between actors throughout the industry is evaluated. The system's integrated nature is explored, looking at synergy's and dependencies throughout the cluster between companies.

Within the Port of Rotterdam, multiple sub-clusters are present that have a constant exchange of waste streams or products. The cluster knows a steam network, chlorine cluster and a network of hydrogen, carbon monoxide and syngas (de Haas and van Dril, 2022). Air Liquide and Air Products are companies with high levels of integrated throughout the cluster, with Air Products' SMR unit being connected to the Esso refinery to enable the continuous exchange of refinery gases and the converted hydrogen, with steam as a by-product. This steam is then sold to Lyondell and Huntsman (de Haas and van Dril, 2022). This example signifies the complex dependencies in the cluster, and is one of many. A non-exhaustive list of dependencies is found in Table 8.

The cluster's governance consists of multiple key actors. Deltalinqs is the representative association of the cluster, representing around 700 companies, lobbying for the common interest of the industry. The Port of Rotterdam Authority is the public-owned facilitator of the industry complex. Knowledge institutes such as the TUDelft and the Erasmus University are part of the SmartPort foundation, generating and sharing knowledge on digitalisation applied to the port and industry.

Table 8: Summary of important dependencies and contributors in the petrochemical, and chemical cluster (de Haas and van Dril, 2022).

Companies involved	Type of dependency
Hexion Pernis, Shell Pernis, Pergen VOF, Shin-Etsu Pernis	Steam, refinery gases
The chlorine cluster; mainly Nobian, Huntsman, Shin-Etsu Botlek, Hexion Pernis, Tronox	Chlorine, HCl, NaOH
Esso Refinery, ExxonMobil RAP/RPP and Air Products Botlek	Refinery gases, hydrogen, steam
Air Products Merseyweg and Air Liquide	Competitive, in the industrial gases/hydrogen and steam markets
Air Liquide and Huntsman/ Ducor/Invista/Lucite/Wilmar Oleochemicals	Steam, electricity, industrial gases
AVR Rijnmond/Cabot and Lanxess/Tronox Pigments/Kemira/Linde Gas Benelux	Steam pipeline connection

The physical connection in the cluster is strong, and the cluster has strong governing bodies, supported by knowledge-institutes. However, through the conducted semi-structured interviews, the social side of the cluster's connection seems to be absent (P1)(P3)(P5). The main reason of this absence seems to be the multinational company types which inhabit the cluster region; The multinational entities formulate global business-strategies, coordinating this strategy throughout the assets. This top-down structure results in a solitary operations in the cluster. Additionally, competition laws severely limit collaborative potential between commercial firms (P4).

The building block is evaluated as *mediocre*. The cluster embodies a variety of strong actors and organisations capable of forming and coordination the network. However, the absence of a social contract is uncovered as the *macro-economic environment* is poor; The closure and production stoppage of various industry players reduce the economies of scale generated by the physical interconnection, possibly enabling a domino effect within the industry (P1)(P3). The stability of the industry is in a critical state (Pals, 2025) (van der Chijs, 2025). With the forecast that more closures are to be expected, the *market formation and coordination* building block will receive more hits in the future. Then again, the variety of strong actors with a vast amount of *knowledge and awareness of technology, and application to market* do have potential for quick development of this building block.

Customers

The customer building block refers to the demand of oil and gas, and therefrom derived products. The petrochemical industry is forecast to be the main driver of further growth of oil and gas demand (Al Mestneer and Bollino, 2024). Without policy intervention, consumption of petrochemical-derived products would continue to grow rapidly (IRENA, 2020). At the same time, the domestic Dutch demand of road fuels are shrinking the fastest in Europe due to electrification of mobility (EAFO, 2025). Additionally, aviation fuels will require 5% of SAF to be blend in, rising to 6% in 2030 (European Commission, 2021). Whilst this keeps kerosene relevant, producers must also invest in SAF production facilities. The earlier mentioned ratio of fuel-types to petrochemical production is thus likely to shift to the direction of petrochemicals.

The customer building block is evaluated as *good*. The global petrochemical demand sees growth potential. However, the state of the *macro-economic landscape* and *competition* forecasts a shift of production of the traditional petrochemical products towards Saudi-Arabia and China. A way to compete with these low-cost producers is essential for maintaining market share (Beacham and de Berry, 2024).

Innovation-specific institutions

The innovation-specific institution building block refers to aspects such as technical standards, fiscal policies and overall governance that is designed around oil and gas. Due to the fossil-dependency that runs through society as a whole, institutions have co-evolved.

Technical standards for fuel quality, safety and refinery processes are based on fossil-based systems, and have developed in parallel. IEA estimated that global fossil fuel subsidies reached 1.3 trillion dollars in 2022, increasing the competitive dominance of oil and gas IEA (2023). Also the Dutch' sector benefits from financial stimulation for the use of fossil fuels, reinforcing said dominance. With the Groningen gas fields shutting down in 2022, the government increased the investment allowance from 25% to 40%, incentivising the production from other gas fields (Elgouacem and Journeay-Kaler, 2020).

However, a pivot is seen in the institutions, with the focus of institutions shifting to decarbonised and renewable alternatives. the innovation institution TKI gas has relaunched as TKI new gas, transforming its portfolio to include 90% hydrogen, green gas, CCS and offshore integration (Gigler and Weeda, 2018). Also the Institute for Sustainable Process Technology's (ISPT) Hydrohub has tripled in membercount in the last five years, signifying this pivot at institutions and market actors (TNO, 2019)(ISPT, 2025).

The European Green Deal, also starts to squeeze the industry out of their traditional market. Due to the implementation of the EU-ETS, as well as mandates in low carbon aviation and marine fuels result in fossil-based operations without a valid decarbonisation pathway to face closure or repurposing. The Dutch implementation of the Green Deal is even more ambitious. On top of the EU-ETS, an extra carbon tax implemented. Additionally, the energy costs and net tariffs in the Netherlands is much higher than in surrounding nations, further hampering the competitiveness of the domestic industry (Pals, 2024).

Whilst the incumbent system still receives favourable policy-making, EU's Green Deal forces the energy transition upon the industry, squeezing the European industry out of the traditional petrochemical markets. The innovation-specific institutions are evaluated as *poor*. The ambitious and progressive stance of the European Union and the Netherlands are part of the *socio-cultural aspects* influencing condition. the influencing conditions *Macro-economic and strategic aspects* as well as *competition* create the stringent market environment.

5.2.2 Evaluation of the Existing Technology Innovation System

The performance status of the Technology Innovation System encompassing oil and gas show an increasingly destabilising system. Whilst the cluster is techno-economically mature, the competitiveness has faded. The ambitious, progress regulatory landscape focused on energy transition has caused competing on the global market to become increasingly difficult. Carbon taxes, and domestic tax top-ups increase the production cost of legacy processes.

The war between Russia and Ukraine has uncovered the energy dependency Europe has, causing energy prices to soar. Combined with the significant cost of Dutch net tariffs, the resulting production costs are significant. Competing with modern, public-funded Chinese petrochemical plants seems impossible in the current situation. With the Middle-Eastern refineries refocusing on petrochemical production instead of fueltypes, the market will be confronted with a flooding of cheap produce.

The vast distribution networks and physical interconnections, once generating economies of scale, now create significant vulnerabilities in the system instead as companies close their producing entities due to the cut-throat climate. The existing technology innovation system has transitioned from maturity into a state decline.

5.3 Technology Innovation System - Low Carbon Hydrogen

The existing technology innovation system encompassing oil and gas has been evaluated. The same process is used to explore the desired technology innovation system of low carbon hydrogen.

Focusing Device

As the goal of this research is to explore how the path theorem can support a system transition toward a system compatible for the application of low-carbon hydrogen in the petrochemical sector, the product group that encompasses 'low-carbon hydrogen' is a suitable focusing device for the focal TIS. Low-carbon hydrogen as product group is limited to the *green* and *blue* hydrogen in this research. The hydrogen colours are related to the production process that is used to produce the element.

Breadth and Depth

The breath and depth includes determining the level of aggregation and the range of applications that the product group includes. The level of aggregation refers to the scale and scope of the TIS. The range of applications refers to the industry in which the focusing device is analysed, as well as the application variety within this industry.

This research focuses solely on the petrochemical industry in a specific geographical cluster. The depth is thus limited to this sector. A sectoral perspective on the TIS captures the industry-specific dynamics in question, enabling the focus on the systemic drivers and barriers that exist within the sector. (Malerba, 2002).

The range of low-carbon hydrogen applications that support the emission-reduction goals stated in the Paris Agreement are of interest. Applications such as those described in subsection 1.1 fit within these boundaries. Substitution of incumbent fossil-based feedstock and fuel, and retrofitting incumbent infrastructure are examples of applications relevant to this study.

Spatial Domain

The spatial domain of the desired technology innovation system is comparable to that of the existing system analysed prior. Spatial constraints have been predicted to constrict the flexibility and decarbonisation options available, validating the selected spatial domain.

5.3.1 Exploration of the Desired Building Blocks

Having scoped the TIS, the seven building blocks can be explored and evaluated. Each building block is introduced shortly, describing what is taken into account per component. At the end of every exploration, the performance of the component is evaluated. If the status of the building block is regarded as poor or mediocre, the causation is further explored by looking at the seven *influencing conditions*. These conditions are described in subsection A.4. Below in Table 9, the building blocks and performance evaluation is summarised.

Table 9: Overview of the low-carbon hydrogen TIS analysis evaluating the building blocks.

Building Block	**Evaluated Performance**	**Influencing Conditions**
Product performance & quality	Good	**Knowledge and technology**: Blue hydrogen can reach sufficient purity after PSA; green H2 is inherently high-grade. **Application and market**: Large-scale hydrogen burners are still emerging; uncertain NOx emissions create permitting issues.
Product price	Mediocre	**Competition**: No price-competition with incumbents; wait-and-see stance driven by other emerging technologies. **Macro-strategic**: EU-ETS + CBAM may enable blue hydrogen for feedstock by 2030; heat applications remain economically unviable.
Production system	Poor	**Competition**: Renewable electricity not dedicated to hydrogen; Electrolyser capacity still low; CCUS potential limited to short-term; Aramis not yet FID-approved.
Complementary products & services	Mixed	**Macro-strategic**: Investments focus on energy transition infrastructure, but hydrogen backbone delayed to 2033. **Application and market**: Industry has hydrogen-handling experience, but large-scale applications remain underdeveloped. **Socio-cultural**: Safety of hydrogen utilities and storage demands extended testing.
Network formation & co-ordination	Mediocre	**Macro-strategic**: Multinational companies choose FID location externally, reinforcing solitary nature of strategy. **Socio-cultural**: Fragmented cluster; social capital is low. **Application and market**: Strong potential from authorities, institutes, and physical connectivity.
Customers	Mediocre	**Application and market**, **Competition**: Wide range of known applications, but uncertainty over which ones will be adopted causes demand-side hesitation.
Innovation-specific institutions	Poor	**Macro-strategic**, **Competition**: Ambitious, yet inconsistent policies destabilise investment outlook. Cluster competitiveness under pressure from global market conditions.

Product performance and quality

The first building block that is evaluated of the TIS of low carbon hydrogen concerns the quality and performance it has in a petrochemical application. Hydrogen, as described in subsection 2.3, has the potential to play a major role in the decarbonisation of the industry. In addition to the use of the element as a feedstock and chemical reactant, hydrogen can be used as a fuel for the energy-intensive processes. The building block is evaluated on purity and process efficiency.

Hydrogen Purity

The purity requirement of hydrogen depends on the application for which it is used(Lubenau et al., 2022). Feedstock applications for example require high-purity hydrogen, whereas furnace burners supplied with a fuel gas mixture do not. The purity required for feedstock application is between the 99.5% and 99.9%. For fuelgas, this concentration is 98%, which is considered low-grade hydrogen (Peters Polman et al., 2023). As blue hydrogen is produced through conventional, hydrocarbon based processes, the process is the same for the production of grey hydrogen. Grey hydrogen requires purification to reach high-grade of hydrogen. Green hydrogen production processes, however, do not require purification (Chang and Rajuli, 2024).

In conclusion, the quality of both types of low-carbon hydrogen is evaluated as *good* for feedstock application and industrial heat generation. The purification process required for blue hydrogen is the same as for grey hydrogen. The *knowledge and awareness of technology* condition thus positively influences the building block.

Process Efficiency

The process efficiency refers to the combustion of hydrogen to enable high-heat processes. At present these processes are fuelled by a fuel-gas mixture, consisting mainly of natural gas. Other gases included in the mixtures are combustible remnants and flue gases from industrial processes. Substituting this mixture with low-carbon hydrogen, or a hydrogen blend, will negate CO2-emissions emitted by the process.

Hydrogen used as a fuel has multiple benefits over using natural gas; the flame is easier to maintain and stabilise because of high flame speeds and wide flammability limits in air. The high spontaneous ignition temperature of 650°C further improves the controllability. However, the high flame speeds create increased flame temperatures, generating higher levels of NOx (Menzies, 2019). NOx, which refers to various nitrogen oxides, is a greenhouse gas similar to CO. Although it is released in smaller quantities by industry, 1 kilogram of NOx has the same climate impact as 298 kilograms of CO2 (CBS, 2025). Therefore, reducing CO2 emissions while increasing NOx emissions is ultimately counterproductive. To make NOx a viable alternative for industrial heat production, its elevated emission levels must be addressed and minimized. Whilst the characteristics of hydrogen seem to be suitable for heat generation purposes, there are still many uncertainties present regarding industrial-scale implementation (ECH2A, 2023). These uncertainties are further explored in section 5.3.1.

To sum up, hydrogen as an element evaluated as *mediocre* for industrial heat generation, but requires adjustments in the process technology to negate the higher levels of NOx and differences in combustion characteristics. The precise extent of elevated NOx emissions remains unclear; the total NOx will reduce, but its concentration in flue gases increase due to reduced flue gasses. These uncertainties create challenges in obtaining the necessary NOx permits (P4). The *knowledge and awareness of technology* surrounding hydrogen combustion is high, but the *knowledge and awareness of application and market* blocks the large-scale adoption the sector requires.

Product price

Product price is an important building block, especially in competitive markets. Emerging technologies experience great difficulties in larger scale adoption when counterparts have lower costs. The price of low carbon hydrogen is explored through production cost. involves costs for acquisition and use of the product.

The price of hydrogen is explored through comparing blue, green and gray hydrogen. The current prices, as well as forecast prices are used to evaluate if the status of the building block is severely lacking, mediocre, or good. The European Hydrogen Observatory have explored the levelised production costs of hydrogen (LCOH). The levelised costs include the capital investment, CO2 costs, natural gas costs and other operational costs. The natural gas costs is also included in the comparison, as hydrogen as a fuel could substitute natural gas. The costs in 2024 are shown in Table 10.

Table 10: Levelised cost of different hydrogen types and natural gas

Type	Levelised Cost (€/kg)	Reference
Green Hydrogen	5.98 - 13.69	(Eblé and Weeda, 2024)
Blue Hydrogen	6.38	(Hyd, 2023)
Grey Hydrogen	6.23	(Hyd, 2023)
Natural Gas	5.38	(Hyd, 2023)

The price of low-carbon hydrogen is not competitive at this point in time. Whilst the low side of the bandwidth given for green hydrogen shows promise, many of the calculative indications done reach costs of over €7 per kg. These levelised costs vary mainly due to different capital cost scopes (Eblé and Weeda, 2024). The calculated costs using specific projects are higher than the more generic studies using ballpark estimates. Blue hydrogen is nearly competitive as a feedstock when compared to grey hydrogen. To be used as a fuel for heat generation, and thus substituting natural gas, requires more time and effort.

Carbon Abatement Cost

In order to estimate the time-frame in which the low-carbon hydrogen types become competitive, carbon abatement cost is adopted as an instrument. The cost-viability of low-carbon hydrogen in European countries can further be analysed through carbon abatement cost. Carbon abatement cost refers to the cost associated with reducing or preventing one metric ton of CO2 (or CO2-equivalent) emissions. This is of economical importance in European countries because of the implemented Emission Trade System (ETS).

The ETS requires industrial firms to pay per ton of CO2 emitted. Payment is done through emission allowances. The allowances are sold in auctions, and can be traded on the market between firms. The total amount of emission allowances reduce overtime, guaranteeing market value as the reducing cap signals long-term scarcity of the allowances. This system motivates companies to decarbonise. If not, their operational costs will increase as the price per ton of CO2 emitted increases. This does however negatively influence European-based industries on a global competition level. To negate this, the Carbon Border Adjustment Mechanism has been introduced. The Carbon Border Adjustment Mechanism (CBAM) is a European regulation designed to account for the carbon emissions embedded in the production of certain goods imported into the EU. It prevents carbon leakage, and ensures a level playing field for EU industries (EU, 2023). This import tax is activated on 2026.

So, if the ETS price is equal, or higher than the abatement cost of a decarbonising technology, the investment breaks even, or is economically profitable. Roxana et al. have analysed the carbon abatement costs (CAC) of green hydrogen, stating that CAC of green hydrogen for petrochemical refinement and ammonia production purposes are estimated at 400$/tCO2 (2024). Blue hydrogen has a CAC of around 100 €/tCO2 for feedstock purposes and 250-300 €/tCO2 for energy purposes (France Stratégie, 2022). Compared to the ETS-pricing forecast visualised in Figure 20, blue hydrogen will be economically feasible for feedstock purposes by 2030 in most scenarios. For industrial heat applications, further development of the hydrogen market is necessary to reduce the costs as the emission price likely wont reach the 300-400 € mark soon.

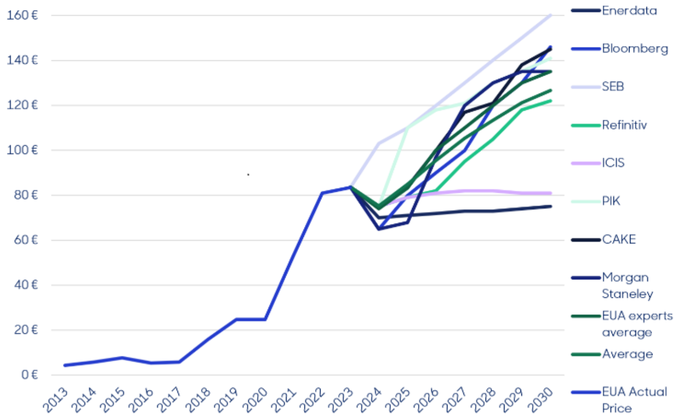


Figure 20: The forecast pricing of European Union Allowances until 2030 (Dimitrova, 2024)

The product price building block is evaluated as *mediocre*. Due to *innovation-specific institution* policy mechanisms influencing the *competition* level of blue hydrogen through levying carbon tax, the product may become viable in 2030. Green hydrogen is nowhere close to reaching competitive price-levels. Regulations mandating the incorporation of green hydrogen in aviation and marine fuels will generate a niche market, but significant economies of scale reducing the price will not enable short-term.

Production System

The envisioned role of hydrogen for decarbonising the industry requires significant amounts of low carbon hydrogen, necessitating significant production capacity. In this building block, the production system for low-carbon hydrogen is evaluated in the present, and foreseeable future. Next to the electrolyser and CCUS capacity, the renewable energy capacity is also considered.

Of the total annual national demand of 1.5 megatons of hydrogen, the entire PoR industry consumes around 644 kilotons per year. This demand is supplied through mainly grey hydrogen (Notermans et al., 2020). To substitute the PoR's gray hydrogen with green hydrogen, an estimated 7.5 GW of electrolysis capacity is required (de Zeeuw, 2024). The Dutch government aspires to achieve an electrolyser capacity of 4 GW by 2030 (RVO, 2020). However, they state that this aspiration is highly unlikely considering the development rate of wind-energy and the shared demand for renewable electricity through direct electrification of emitting infrastructure. The goal to increase the domestic wind-energy capacity from 11GW to 29GW by 2030 has been postponed to 2032, pushing back dependent hydrogen production projects (Planbureau voor de Leefomgeving, 2024). PBL's report further states that reaching the set 2030 goals only have a 5% chance of being reached. Currently only one significant electrolyser project has reached it's construction phase. Shell's Holland Hydrogen One project is a 200MW electrolyser plant, starting operations in 2025 (Shell, 2022). In conclusion, the domestic production of significant amounts of green hydrogen is not feasible in the near future.

Looking outside the domestic production, the international production systems designed for green hydrogen export are also inadequate. The Dutch import of green hydrogen in 2030 is unlikely (Elzenga and Strengers, 2024). The development of elektrolyser capacity worldwide is lacking, causing delays in reaching the capacity necessary (de Zeeuw, 2024).

To produce blue hydrogen, the emitted CO2 must be captured. With an emission factor of 9kg CO2/kg H2, the annual capture, transport and storage or utilisation capacity required for PoR's demand is approximately 5,8 Mt (de Zeeuw, 2024). Currently, two major CCUS projects are in development domestically.

The Porthos, a major CCUS project in the Port of Rotterdam, is currently in development. This project allows for the storage of a total 35 Mton CO2 by capturing the CO2 in the industry sector and transport it to depleted natural gas fields in the North Sea, storing 2.5Mt annually for 15 years. This project results in a temporary CO2 reduction in the Port of Rotterdam of 10% for 15 years and will start operations in 2026 (Royal HaskoningDHV, 2020). Aramis, the second major CCUS project is still in the design stage, but is projected to have a capacity up to ten times greater than Porthos. Together, these projects can offer long-term storage of CO2-emissions, enabling the production of blue hydrogen.

Whilst already allowing for short-term decarbonisation of the industry, the CCUS capacity nor the electrolyser capacity is sufficiently developed to reach the long-term decarbonisation goals. The building block is evaluated as *poor*. Blue hydrogen's potential role as a short-term decarbonisation tool can be enabled with the current forecast of carbon capture facilities, but the production capacity for green hydrogen needs to be accelerated. The *competition* influences the usage of the present renewable energy, as it is not dedicated to green hydrogen production.

Complementary products and services

This building block evaluates the availability of complementary products and services supporting the development, production distribution and adoption. As this building block has a wide variety of factors incorporated, For this study, the building block is tailored down. The building block is evaluated through the complementary products and systems that are necessary for adoption: Distribution systems, storage systems, and utilisation systems.

Distribution Systems

Besides the production being of obvious importance for low-carbon hydrogen to become a viable choice, the distribution networks are of equal importance. For example, RWE and Oranjewind are postponing their final investment decision (FID) for a 50MW and 100MW elektrolyser until the national distribution systems are ready (Abele, 2024). This postponement signifies the essential role distribution has in the transition. The postponement can also damage the collective expectations of hydrogen's role in the energy transition, losing its competitiveness relative to other decarbonising options.

Hydrogen can safely be blend in with natural gas pipelines up until 20%. Blending in more hydrogen would require major retrofits (Deloitte, 2023). A blend of 20% will not result in large decarbonisation of the industry, and thus the distribution system needs to be customised. Currently, The Netherlands knows two private hydrogen distribution networks, both located in the PoR. These distribution systems are used for connecting hydrogen refineries with industry consumers. In 2022, the Dutch government initiated the development of a hydrogen backbone, interconnecting the six Dutch industry clusters together with the neighbouring countries. This hydrogen distribution network, named HyNetwork, is essential infrastructure for enabling the hydrogen economy. As mentioned in section 1, this project is delayed, and instead of completion in 2030, the project is delivered at the end of 2033 (Hynetwork, 2024).

In Figure 21, the status of the distribution network in 2030 is shown. Hydrogen import by boat becomes possible, but a hydrogen economy in the Netherlands and its neighbouring countries is not yet feasible. This economy is essential to create a more cost-competitive product, and thus now negatively impacts the development of the TIS. However, the postponement is well analysed, and the certainty of the new deadline is relatively high (Hynetwork, 2024). The distribution system is evaluated as *mediocre*. The future investments seem to all focus on the repurposing of distribution systems, or the construction of new infrastructure for energy transition purposes (Gasunie, 2024). The building block's development is positively influenced by the *strategic aspects*.

Figure 21: National distribution system status in 2030. At the end of 2033, the distribution system is linked together, enabling exchange between clusters and with the Ruhr-area (Hynetwork, 2024).

Storage Systems

With the intermittent nature of the renewable energy sources, sufficient storage capacity is essential for the stability and flexibility of the hydrogen system. Hydrogen storage systems are thus very important for green hydrogen. Hydrogen storage is a difficult concept because of the low energy density and high diffusivity properties it possesses (Mulky et al., 2024). Large, scalable storage can be realised in underground salt caverns. Smaller, more decentralised storage solutions such as compressed hydrogen and liquid hydrogen are also feasible, whilst being more costly. Revinova et al. state that hydrogen storage in salt caverns is the most promising method considering the technology readiness level as well as the relatively low storage costs (2024).

HyNetwork, the national hydrogen distribution system, includes HyStock. HyStock is a large-scale underground storage facility utilising an old salt cavern in the north of the Netherlands (Figure 21). This storage facility enables storing 20kT of hydrogen. TNO estimates that on-shore Dutch salt caverns can hold another 43 TWh of hydrogen (14,5 billion m3), with only a necessary storage capacity of 1.5-2.9 TWh to suffice to the system demand in 2050 (Groenenberg et al., 2020).

The storage system is evaluated as *good*. The condition influencing the development of the building block component is the *knowledge and awareness of application and market*. The technology readiness level still needs to be improved further to decrease uncertainties surrounding the storage technologies. Safety requirements (*Socio-cultural aspects*) further emphasise the need for secure storage and utilisation, necessitating high amounts of certainty to be implemented.

Utilisation Systems

Utilisation systems refer to the necessary systems through which the hydrogen can be applied. For example, using hydrogen as a fuel for heat production requires a compatible combustion system, consisting out of subsystems such as burners, fuel lines, and measuring equipment. The properties of hydrogen differ from the traditional used fuel gas, requiring adjustments to be made (Menzies, 2019).

The Technology Readiness Level (TRL) of hydrogen combustion for heat production purposes is between the 6 and 7; 100% hydrogen fuelled boilers are successful in <1 MW boilers, but there is a lack of larger capacity demonstrations, resulting in a TRL level of 6 (Hydrogen TCP, 2023a). Flexible H2/NG burners (0-100% H2) allow for a wide variety of hydrogen concentration in the mixed fuelgas. These burners are still in the demonstrative phase, as little to no burners are on the market. Flexible burners have a TRL of 6-7 (Hydrogen TCP, 2023b).

It is likely that as the market for hydrogen becomes more stable and prominent, the complementary storage and utilisation systems will develop similarly. The national distribution system being delayed has 'awarded' the wait-and-see mentality, harming the development of the overall innovation system. The *complementary products and services* building block is evaluated as *mediocre*. The *existing knowledge and awareness of technology* present in the cluster due to the established hydrogen producers such as Air Liquid and Air Products boost the development of proven technologies. *New markets and applications*, such as large-scale storage and large-scale burners require more research, creating uncertainty.

Network Formation and Coordination

Establishing the supply chain necessary for large-scale low-carbon hydrogen use requires network formation and coordination. Besides the collaboration between market actors, a shared vision between these actors is important. Collective expectations and vision within the industry regarding what decarbonisation route is optimal drive infrastructural, technological and market development (Storbacka and Nenonen, 2015).

Currently, the industry's coordination status is similar to the *chicken and egg* dilemma; The industry does not invest in hydrogen-based technologies due to uncertainties in supply, whilst companies avoid developing hydrogen production capacity because of uncertain future demand (Dulian et al., 2025).

Hydrogen project initiatives have been facing multiple challenges, of which the most significant is the navigating the *innovation-specific institutions'* regulation landscape (P1)(P2)(P3)(P4)(P5). Also the clash of company cultures and individual agenda's complicate coordination attempts (P2)(P3). Furthermore, it is only recent that companies in the focal cluster increased the collaborative initiatives. This is mainly due to the ability to pool uncertainties and capital, reducing the risk of the project (P4)(P5).

The cluster has a vast physical network, connecting companies inter- and intra cluster. The formation of a cluster hydrogen economy has potential. The Port of Rotterdam Authority states envisioning to become 'Europe's Hydrogen Hub' (Port of Rotterdam, 2020). Parading hydrogen has influence on the collective expectations, legitimacy and the technology's reputation, and may attract like-minded organisations and firms, boosting the formation of the network.

The building block is evaluated as *mediocre*. No low-carbon hydrogen ecosystem has formed, and coordination is still fragmented. However, many components for creating and coordinating the network are present. the current regulation landscape is the main barrier blocking development of the TIS due to its fluctuating, complex and constricting nature. Whilst ambitious and desiring the development of the TIS (*socio-cultural aspects)*, effective policy implementation remains difficult. *Knowledge and awareness of application and market* remain uncertain as the shape of the emerging markets is unknown (P5).

Customers

Customers consuming low-carbon hydrogen is essential for development of the innovation system. With the business-to-business type of market which the petrochemical industry characterises, customers are situated down the value chain. Currently, hydrogen is used mostly used as a feedstock for ammonia and methanol, and used in refineries for oil refining processes. Future uses of hydrogen products will cover many other different end uses; Synthetic transportation fuels for mobility and aviation, which are based on renewable hydrogen, increasing the hydrogen demand (Detz et al., 2019).

For the production of industrial heat, hydrogen can be blended into the natural gas network for decarbonization, or act as a substitute completely. 90% of the studies analysed by Detz project hydrogen to provide high temperature heat, further increasing hydrogen demand. However, alternative high-temperature heat technologies are emerging, creating uncertainty in the actual share of hydrogen use. Additionally, technology such as Fischer-Tropsch synthesis and methanol synthesis are fit for substituting fossil-based feedstocks (Gigler and Weeda, 2018). Implementation of such technologies can substitute the consumption of fossil resources and produce carbon-based products such as hydrocarbons and base chemicals .

In the meta-analysis done by Detz, the range of hydrogen use from 25 different studies is analysed. This comparison shows the wide variety of envisioned future demand; in 2030, an annual consumption of 0 to 3.2 Mt is forecast. in 2050, the hydrogen use is envisioned to reach an annual consumption of 0 to 16 Mt. The wide bandwidth present in the various studies show the uncertainty present in how hydrogen will be applied.

The building block is evaluated as *mediocre*. There is significant potential for a large customer base, but due to lacking *knowledge and awareness of application and market* and future *competition* generate uncertainty.

Innovation-specific institutions

Innovation-specific institutions refer to the formal and informal rules present in government policies, laws, standards and regulations. For this building block, the current state of policies, standards and regulations are explored.

The European Commission's Green Deal is the ambitious energy transition plan relevant to all its members. Whilst well formulated, with the translation towards member states this has not been the case (P3). This has resulted in fluctuating policies and regulations, making the navigation increasingly complex. Additionally, the domestic regulations have been even more ambitious than the European regulations, introducing a top-up carbon tax and increasing net-tariffs (Pals, 2024). Besides having trouble being competitive on the global markets, the Dutch industry also experiences a uneven playing field on European level. The Carbon Border Adjustment Tax (CBAM) mechanism, enabled in 2026 attempts to level the global playing field by carbon taxing products being imported into the EU (EU, 2023). The effectiveness of this policy is still unknown (P1) (Draghi, 2024).

The most prominent policies influencing the hydrogen innovation system are EU's Red Energy Directive (RED) III and the Dutch Climate Agreement, pressuring and driving the industry to adopt decarbonising solutions, including low-carbon hydrogen options. RED III requires a 1.6% annual increase of renewable energy in industry, as well as 42% of hydrogen used to be substituted for Renewable Fuels of Non-Biological Origin (RFNBO) in 2030 (European Commission, 2021). RFNBO's are a category of renewable fuels which primarily consist of synthetic fuels, of which most are hydrogen-based. This annual increase and substitutive measures steer hard-to-abate industries towards developing the low-carbon hydrogen value chain. The RFNBO percentage increases to 60% by 2035, creating longer-term certainty on hydrogen-related investments.

The regulatory situation is however also constraining further development of hydrogen projects. Uncertainties regarding the role of carbon capture and blue hydrogen remain a large bottleneck towards making a positive final investment decision (Rijksoverheid, 2024). Due to the mandates, the European industry is squeezed out of their traditional markets. Due to the ongoing geopolitical events *(accidents and events)* and harsh *macro-economic and strategic aspects* described in subsection 5.2, the industry might not survive the transition phase.

The standardisation activities of hydrogen featuring industry and process heat are challenging as there is no one-size-fits-all solution for substituting the current heat source with hydrogen produced heat (ECH2A, 2023). The standards of both hydrogen blends, and 100% hydrogen (material use, safety measures, performance, emissions, ...) have yet to be updated to incorporate the emerging applications. This results in uncertainty regarding combustion processes, efficiency, and impact on emissions reducing the likelihood of hydrogen adoption for industrial heat. Standardisation of hydrogen also creates the basis for certified burners and other specific necessary technology, boosting the development of other building blocks such as *complementary products and services*.

The building block *innovation-specific institutions* is evaluated as *poor*. Fluctuating domestic regulations harm the *competitiveness* of the industry on the traditional markets, whilst creating uncertainty for the development of the desired TIS. The current *macro-economic and strategic aspects* and *competition* conditions negatively influence the building block.

5.3.2 Evaluation of the Desired Technology Innovation System

The seven building blocks of the desired Technology Innovation System encompassing low carbon hydrogen as a product group have been explored and evaluated. Using the influencing conditions, an effort is made to anticipate whether the building block is likely to progress or decline. Overall, the system is in an insufficient state to allow for large-scale adoption of low-carbon hydrogen.

The largest performance gaps are seen in the *Production system* and *Innovation-specific institutions* building blocks. Due to the complex, and constantly fluctuating regulatory landscape, long-term investments characterised by high capital costs, possess too much risk and uncertainty to be viable. Mainly due to this reason, initiatives for large-scale production systems have rarely made a positive FID. Without enabling the production systems' economies of scale, the product price will remain too high to compete with incumbents. The postponement of the hydrogen backbone also postpones the formation of a domestic hydrogen market, hampering the access to potential demand.

The cluster is part of an ecosystem with a lot of potential; the geographically strategic location in one of the largest ports of Europe, governed by the Port of Rotterdam authority stating the vision to become Europe's hydrogen hub. The cluster inhabitants are actors with a vast amount of knowledge and awareness on both technology, as its applications. The development of the *network formation and coordination* building block has a lot of potential to be developed quickly. However, the solitary nature of the multinationals need to be addressed to enable alliance building. Incorporating social capital, and creating a collective vision may assist in creating a domestic market for low carbon hydrogen.

5.4 Conclusion

In this section, the goal was to diagnose the current, and desired Technology Innovation System. By exploring the seven building blocks of the respective systems, the present condition as well as the anticipated developments are examined.

The incumbent oil and gas TIS has, over its long time-span of being the dominant system, generated significant techno-economic maturity. This maturity however, seems to be moving to a phase of decline. The petrochemical industry in the Port of Rotterdam is exposed by an increasingly challenging macro-economic landscape. The combination of modern facilities being built abroad, enjoying low production costs, and domestic ambitious energy transition policies squeezing the cluster out of the status quo which has destabilised the incumbent TIS. With energy costs and net tariffs soaring, the cluster is in survival mode. Whilst policies further pressure transitioning and penalising the status-quo, the situation is unsustainable.

Whilst this may sounds optimal for reaching the desired TIS, attempting to transition is largely impossible. Whilst hydrogen is well-understood technically, the necessary complementary products and services are not yet ready to facilitate the creation of a domestic hydrogen economy. The emerging markets and networks are still in an infant stage, creating uncertainty and suppressing cluster coordination. Substitution of grey hydrogen with low carbon substitutes has not reached a competitive price point, thus not enabling off-take. Regulations, whilst ambitiously wanting to enable the energy transition, are in constant flux, complex and ineffective.

With the incumbent system destabilising, and the successor not ready to take over, the industry is in a critical state. Whilst an unstable system creates the opportunity for dismantling the building blocks, reallocating the resources towards the desired system, a clear envisioned structure of said system is essential to effectively guide the transition process.

6 Path Dependency in the Port of Rotterdam

6.1 Introduction

In this chapter, the path dependency part of the path theorem is focused on. This focus is visualised in Figure 22. The goal of this section is to understand the effect the past has on the present in the petrochemical cluster of PoR. The cluster dynamics sustaining the status-quo analysed in subsection 5.2, and preventing the development of the desired TIS building blocks analysed in subsection 5.3 are uncovered and analysed. Whilst these underlying causes have partly been found by exploring the influencing conditions of the respective TIS, insight regarding the more unique characteristics and dynamics of the PoR petrochemical cluster is gained through the semi-structured interviews with market actors. The question to be answered in this chapter is:

"What are the industry dynamics, and self-reinforcing mechanisms specifically, influencing the path trajectory of a TIS transition in the petrochemical industry?"

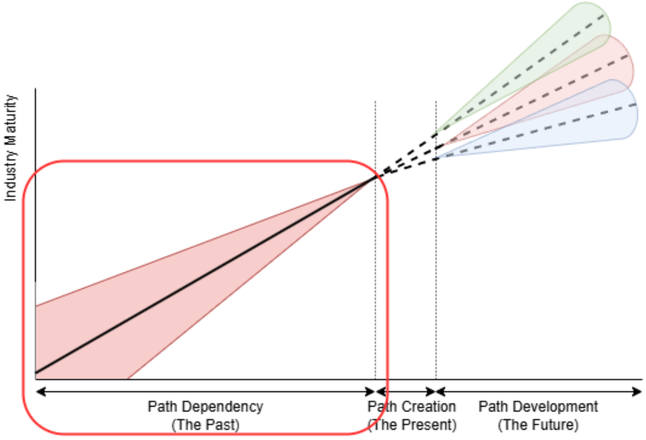


Figure 22: The path dependency part of the path theorem focused on in section 6

First the cluster dynamics are described, after which these will be dissected into self-reinforcing mechanisms and the underlying lock-in sources. The translation towards the TIS-framework is made to enable systematic uncovering of the components with path creation potential in section 7. The cluster dynamics are explored in subsection 6.2. These dynamics are dissected into three self-reinforcing mechanisms and their respective lock-in sources in subsection 6.3. Finally, this section's question is answered in subsection 6.4, providing an overview of the path dependency present in the petrochemical cluster of PoR.

6.2 Cluster Dynamics: Paradoxical Interdependence

The dynamics that characterise the petrochemical industry in the Port of Rotterdam can influence the development of the desired technology innovation system. In this section, the dynamics characterising the cluster are described.

Whilst the cluster has physical systemic integrations through dedicated (private) pipelines and the established heat- and steam exchange systems, this integration isn't created through the producing entities (P3)(P5). Companies make decisions based on their own global business strategies, with minimal coordination across the cluster (P1)(P3)(P5). These global business strategies are formulated in high-level, multinational corporate governance, and translated through to the internationally established assets. Due to this top-down approach, the petrochemical industry is comparable to islands; individual, on-site development is the main focus (P2)(P3)(P4)(P5). P3 states that the original reason for the establishment of these plants are due to the geographically and strategically strong position of the port; the accessibility for large tanker transport ships and the direct connection to the ARRRA-cluster allows for large-scale transport from the upstream suppliers, towards the downstream customers. The system integration was thus not created by the producers themselves, but through the entry of complementary service providers and utility firms into the cluster (P3).

The exclusive physical interconnection also create vulnerabilities in the system. The decision to stop production and exit the market is made on the same global level as the strategy is formulated (P3)(P4)(P5). Especially during the current harsh macro-economic conditions, the chance of this happening is increased. The exit of an actor can cause a disturbance in the system integration of waste/product flow, damaging the productivity and efficiency of interconnected actors. Due to the same harsh macro-economic conditions, this disturbance can result in a domino-effect, rapidly shrinking the existing industry. P5 states that these interconnections are not always visibly present, comparing the scenario to a Jenga puzzle; taking away one piece of the puzzle may reveal yet to be seen vulnerabilities. This Jenga puzzle covers more than just the PoR cluster, but also the ARRRA-cluster, and other dependent facilities such as (military) airports (P3)(P5) (Pals, 2025).

Due to the strategy formulation taking place on a higher level than the cluster, the long-term vision of the multinational lies outside the cluster. The strategies of the locally established firms are more focused on short-term goals, such as established production and optimisation goals (P3)(P5). Combined with the fluctuating regulation climate and harsh macro-economical conditions generating long-term uncertainty, the companies are further inclined to focus on the on-site, short-term gains (P5) (Souder et al., 2016). This dynamic can further entrench the solitary behaviour.

Dynamic Pivot

However, a change in this dynamic can be observed. Energy-transition related projects are shrouded by uncertainty and risk, coming forth from new types of technologies and markets (P1)(P3)(P5). Additionally, the scale of these projects cost-wise are up to a tenfold larger, further adding project management complexity (P5). In order to mitigate the risks, more attempts at collaborations are seen (P2)(P4)(P5). Other mentioned benefits are the combined competencies and expertise, increasing technological and management know-how (P2)(P4)(P1), further reducing the risk.

Attempting collaborations remains complex. Organisational cultures vary between companies, resulting in conflicts in collaborative forms (P2). Additionally, due to being market competitors, competition laws severely limit the level of collaboration possible (P3)(P4). P4 does state that the involvement of a neutral party greatly helps in facilitating a collaboration, and that the existence of parallel private agenda's is to be accepted in order to create collaborations. Furthermore, attracting the attention of multinationals to motivate significant investment is a responsibility of the national institutions (P3); establishing a stable investment climate, surrounded by an innovative ecosystem advertises the cluster for innovative investment decisions (Ivanovski and Marinucci, 2021).

Translation to the TIS-framework

Translated to the TIS-framework, the *network formation and coordination* building block possesses inherent systemic barriers. Due to the majority of the industry actors being multinational organisations, the cluster's network is fragmented, characterised by an island-based structure. The long-term strategic decision-making sits outside the cluster, resulting in a lack of shared investment horizon within the cluster.

The network formation and coordination that does exist seems to have been created by utility and service providers. In this case, the *complementary products and services* building block seems to be connected to the *network formation and coordination* building block. Additionally, attracting investments requires the national institutions to create a stable investment climate for energy-transition projects. The building block *Innovation-specific institutions* thus also influences the *network formation and coordination* building block. The innovative ecosystem boosts the attractiveness of the investment climate. The influencing conditions *knowledge and awareness of the technology* and *knowledge and awareness of application and market* thus have an effect on the cluster dynamic. The TIS connections are visualised in Figure 23.

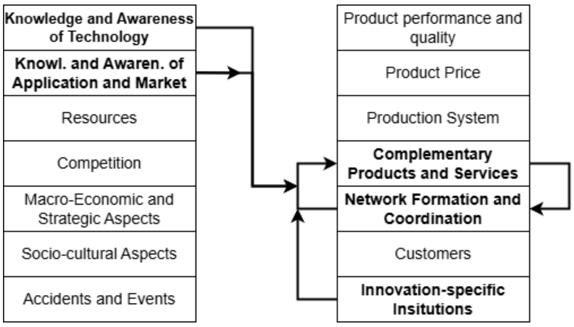


Figure 23: The Paradoxal Interdependence cluster dynamic visualised through the TIS-framework.

6.3 Self-Reinforcing Mechanisms

The analysis of both the incumbent technological innovation system (subsection 5.2), as of the low-carbon hydrogen types (subsection 5.2) has highlighted the development status of the seven building blocks, and explored the causes underlying development-inhibiting barriers. To gain a more in-depth understanding of the dynamics in the cluster, self-reinforcing mechanisms are theorised. These self-reinforcing mechanisms are derived from the cluster dynamics explored in subsection 6.2. The lock-in sources underlying the self-reinforcing mechanisms are also connected, completing the question's scope.

6.3.1 Green Flings

A recurring dynamic is the fluctuating engagement of petrochemical industry has had with the low-carbon hydrogen innovation system in the Netherlands. This fluctuating engagement is mainly caused by weak innovation-specific institutions (P1)(P2)(P3)(P4)(P5). The lack of a stable vision regarding the development of the low-carbon hydrogen TIS, and what tools are available to reach set decarbonisation goals generate uncertainty within the industry.

Another possible cause for the fluctuating engagement is the level of competitiveness of low-carbon hydrogen compared to alternative decarbonising options. Electrification of emitting infrastructure is a major contender in the petrochemical industry to substitute the conventional technology; industrial heat generation is possible through electrification and hydrogen combustion. The *technological incompatibility* between electrification or hydrogen implementation is a lock-in source of this competitiveness nature (Janipour et al., 2020).

This fluctuating engagement is similar to the *green flings* as described by Mäkitie et al (2019). Green flings are likely harmful for the long-term development of the TIS in question. The system resources *collective expectations* and *technology reputation* surrounding the technology's dominant role in the decarbonisation of the industry are impacted negatively by the postponements and cancellations. The impact on collective expectations and technology reputation can negatively influence other projects developing one or more building blocks of the desired TIS, which increases the likelihood of another of these projects being postponed or cancelled. This, in turn, again impacts the collective expectations and the technology's reputation, deteriorating the formation and coordination surrounding the technology.

This deterioration causes the decarbonisation vision to steer away from the role of low-carbon hydrogen. The resource erosion affects the decision-making within the innovation-specific institutions, reorienting decarbonisation-incentivising policy, again impacting ongoing projects. This cycle is visualised in Figure 24.

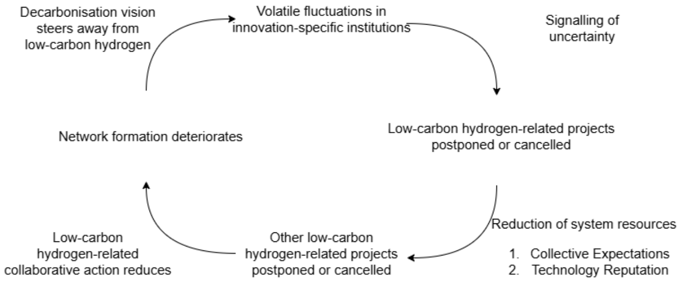


Figure 24: Green fling self-reinforcing mechanism, including the key factors and effects each have.

The green fling is a self-reinforcing mechanism eroding network-, and system resources, reducing the competitiveness and trust regarding its decarbonising potential. This leads to a 'lock-out' type of lock-in; the envisioned viability of hydrogen as a contributor in the decarbonising efforts will deteriorate overtime. The underlying lock-in sources are *Technological incompatibility* and *Policy Inconsistency*; The policy inconsistency enables the green fling, whilst the technological incompatibility present between hydrogen and alternative decarbonisation options causes the locked-out result.

TIS Translation of the Green Fling

The dynamics of the green fling mechanism can be translated to the TIS-framework. The underdeveloped building block *innovation-specific-institutions* bottlenecks and affects the building block *network formation and coordination*. The connection between the two building blocks have a negative influence on the state of the influencing conditions. Resources are mobilised away from low-carbon hydrogen-related projected. The social attention (socio-cultural aspects) also shifts away from the role of low-carbon hydrogen. The deterioration of the influencing conditions directly damage the already underdeveloped building blocks. The effects have been visualised in Figure 25.

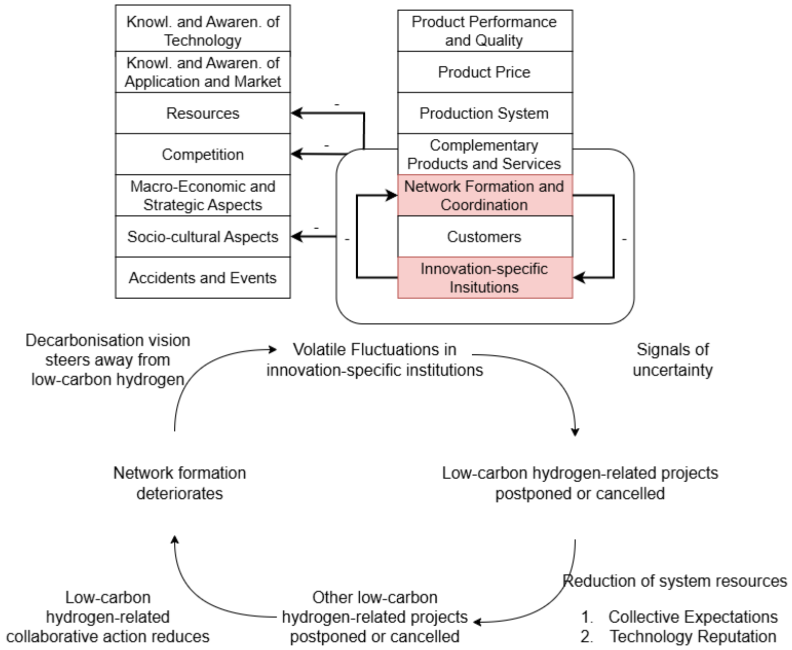


Figure 25: The Green Fling self-reinforcing mechanism described through the TIS-framework.

6.3.2 Incrementalism Trap

In the interviews, energy efficiency investments are stated to be 'no-regret' decisions (P2)(P4)(P5). Additionally, these participants state that energy efficiency projects should be prioritised over energy transition projects. The philosophy is that better utilisation of process streams will lower required current, and future input streams such as feedstock and energy. The example given is that better utilisation of waste heat will require less combustion of natural gas now, and less hydrogen combustion in the future. Moreover, firms must continuously optimise their existing processes to remain competitive in a commodity market; otherwise, they will not survive long enough to pursue large-scale, radical decarbonisation initiatives (P5).

Whilst this approach is sensible, the investments in energy efficiency create short-term decarbonisation gains, but not the envisioned, long-term 'deep' decarbonisation gains necessary on the longer term (Verdolini et al., 2023). The improvement of energy efficiency is an incremental investment made on existing infrastructure. On a company level, this extends the viability of the infrastructure, extending the lifespan and prolongs the competitiveness by lowering production cost. However, it also widens the gap in performance compared to low-carbon alternatives, increasing the switching costs. This dynamic is similar to the phenomenon *strategic drift*; the company is unable to adapt in alignment with the changing environment, harming the market-viability of the company (Johnson et al., 2010).

On a cluster level, these incremental investments can create a *incrementalism trap*; cluster synergies are improved, which increases the interdependency between companies. This interdependency causes an increased complex decision-making process regarding more disruptive low-carbon investments (Janipour et al., 2020). Further clusterisation increases the potential incremental improvements, which promotes incremental investments, again increasing the clusterisation. This cycle leads to a technological and coordination lock-in. The self-reinforcing mechanism is visualised in Figure 26.

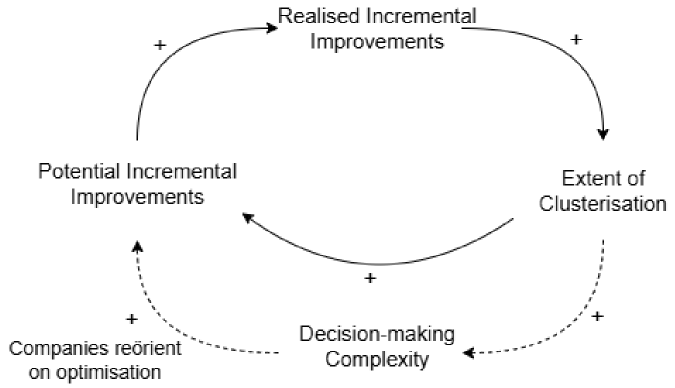


Figure 26: The 'Incrementalism Trap' self-reinforcing mechanism, adopted from (Janipour et al., 2020)

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The lock-in sources underlying the mechanism are *system integration* and *sunk costs*. The increasing physical interconnection facilitate the enabling of the increasing complexity of decision-making regarding disruptive low-carbon investments. The sunk costs of maintaining and upgrading incumbent process technologies, lengthening the life-span significantly, economically demoralises actors to switch to alternative technologies due to stranded assets. The substantial capital already committed to maintaining and upgrading existing processes, thus extending the asset's operational lifespan, makes the risk of stranded assets financially discouraging, inhibiting the adoption of alternative technologies.

Decision-making complexity factors

The *Incrementalism Trap* self-reinforcing mechanism, originating from the system integration lock-in source, makes decision-making regarding investments in disruptive technologies more complex. A more complex decision-making process slows down collaborative projects; collective expectations and goals of the project become harder to formulate, decreasing collaborative potential. For ongoing projects, it increases the chances of postponement or cancellation of a project. This complexity is highlighted in the petrochemical cluster of Rotterdam, as joint-venture projects face many challenges throughout the development stages (P2)(P4).

These challenges include the complexity of clear role distribution, and differences in company culture and company structure (P2)(P4). Examples given for the difference in company structure and culture is the controversy generated by the collaboration between commercial-oriented companies and semi-public organisations for the production of distribution and storage infrastructure. The definition of success varies between different types of organizations (profit vs more public valued aspects), complicating the development of collective expectations. Additionally, two market players may face competition laws when attempting to collaborate, forcing non-transparent partnerships (P4)(P3).

Larger commercial petrochemical companies usually have more margins to afford predictive maintenance approach. Collaborating with differently oriented companies that adopt a more reactive maintenance approach can prove difficult as such approaches are translated throughout the company's culture (P1)(P2). In the current harsh macro-economic environment, larger companies with greater financial resilience are better equipped to tolerate market volatility than their smaller counterparts. This uncertainty can strain or even break collaborations, depending on each company's ability to withstand economic pressure.

TIS Translation of the Incrementalism Trap

Similar to the green fling mechanism described in subsubsection 6.3.1, the incrementalism trap self-reinforcing mechanism can be described through the TIS-framework. Macro-economic conditions are harsh, and companies are strategically searching for short-term gains. The focus on the short-term is expressed in the urge to fall back on core business markets, and optimisation investments. This type of investment on a inter-organisational level increases the complexity of decision making on more disruptive technology investments, harming the network formation and coordination. Additionally, the macro-economic conditions and EU's competitive state are partly caused by the poor state of the innovation-specific institutions building block (Draghi, 2024). The connection between influencing conditions and building blocks is visualised in Figure 27.

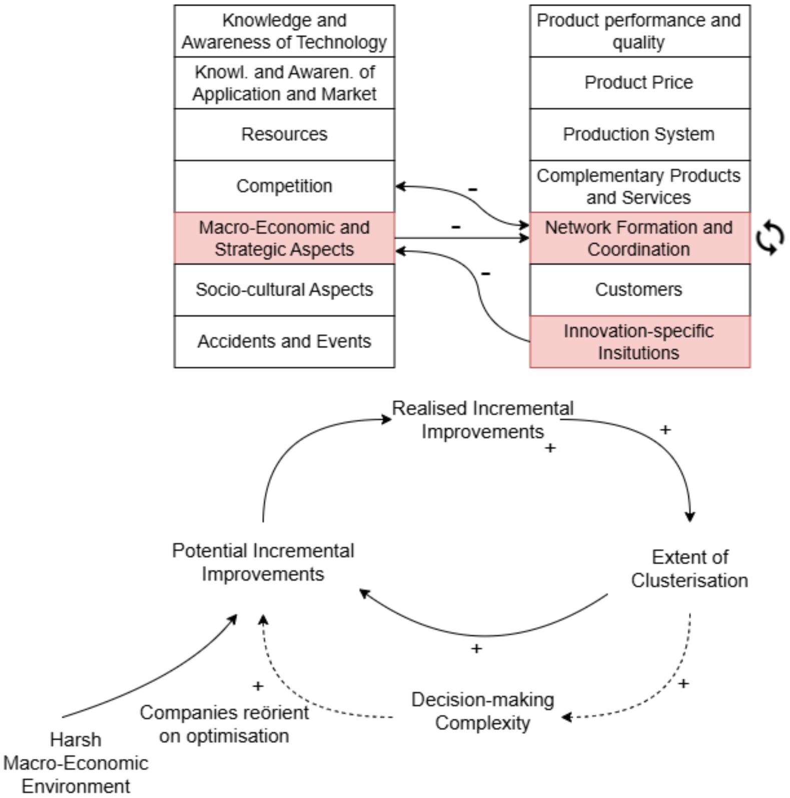

Figure 27: The Incrementalism Trap self-reinforcing mechanism described through the TIS-framework.

6.3.3 Solitariness Trap

The solitariness trap suggests that the absence of a shared sustainable cluster strategy hinders the development of collaborative initiatives, and the lack of such initiatives, in turn, prevents the formation of a shared strategy (Janipour et al., 2020). The paradoxical interconnection dynamic present in the cluster enables the solitariness trap; high-level hierarchical governance has shaped the cluster into a series of isolated islands. Despite their physical interdependencies, this fragmentation prevents the formation of substantive alliances (P1)(P2)(P3). Firms within the Port of Rotterdam primarily concentrate on short-term objectives, with a particular emphasis on improving energy efficiency at individual sites.

Figure 28: Visualisation of the Solitariness Trap self-reinforcing mechanism (adopted from (Janipour et al., 2022)

TIS Translation of the Solitariness Trap

Translating the solitariness trap to the TIS-framework results in a feedback loop within the *Network formation and coordination* building block; When there is no coordination, there is no formation. When there is no formation, there is no coordination. The poor state of the *Innovation-specific institution* building block affects this feedback loop by not effectively incentivising network formation and coordination of the desired TIS.

The *Resources* influencing condition has a positive feedback loop with the *Network formation and coordination* building block due to the generation of network- and system level resources. The development of the building block requires, but also creates said resources due to network economics enabling increasing returns to adoption. If a network stops being coordinated, it deteriorates as resources dwindle. However, the incumbent TIS is held stable by powerful actors with an private or corporate interest, prioritising the survival of its system network (Goldstein et al., 2023). This results in a **Incumbent anchoring** type of lock-in, where these powerful actors with vested interests actively maintain the status-quo.

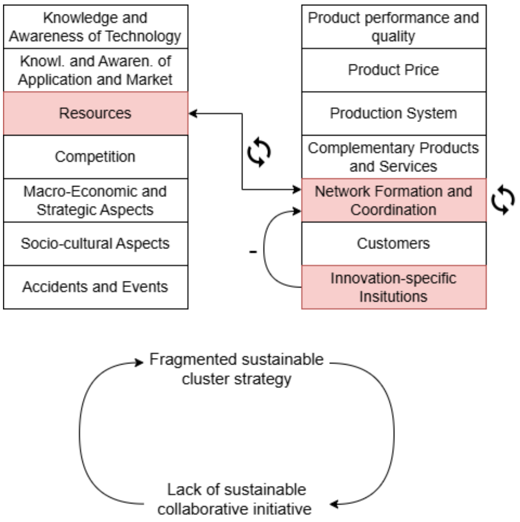

Figure 29: The solitariness trap translated to the TIS framework.

6.3.4 Self-Reinforcing Mechanism Interconnections

1. **Interconnection between Incrementalism Trap and Green Fling** - The incrementalism trap described by Janipour et al. may be interconnected with the self-reinforcing mechanism explored in subsubsection 6.3.1; a reduction in collaborative action caused by an increase in decision-making complexity has a negative impact on the building block 'network formation and coordination' of the focal TIS. If collaborative action in decarbonisation routes decrease, companies reorient to on-site improvements, leaning towards optimisation.

2. **Interconnection between Incrementalism Trap and Solitariness** - An interconnection between the incrementalism- and solitariness trap is observed. Due to the incrementalism's increased decision-making complexity in radical innovation collaborations, the firms are pushed towards site-level optimisation, harming network formation and coordination. This market fragmentation deepens the absence of a shared cluster strategy, characterising the solitariness trap.
3. **Interconnection between Green Fling and Solitariness Trap** The green fling and solitariness trap may also have an influence on one another. The erosion of network- and system resources damage the network formation and coordination surrounding the technology. Due to the already fragmented cluster vision (solitariness trap), the resilience of the resources when experiencing setbacks is weak, increasing the effects of the green fling.

Triangular Interconnection

Having identified multiple bilateral interconnections between the self-reinforcing mechanisms, a mutual component is observed. All three self-reinforcing mechanisms affect the network formation and coordination, essential for cluster coordination, alignment of expectations, pooling risk, and mobilising network- and system level resources. This interconnection is visualised in Figure 30

Incrementalism complicates decision making, driving investment decision-making towards solitary, on-site incremental innovations. These incremental innovations increase the performance gap between current and emerging process technology. Additionally, it consumes the rare investment decision-making window by increasing the assets lifespan.

Green flings demoralise collaborative initiative of developing the desired TIS. The solitariness trap increases the level of demoralisation per green fling cycle, due to the absence of both a long-term cluster strategy and alliances. This absence creates a lack of setback resilience.

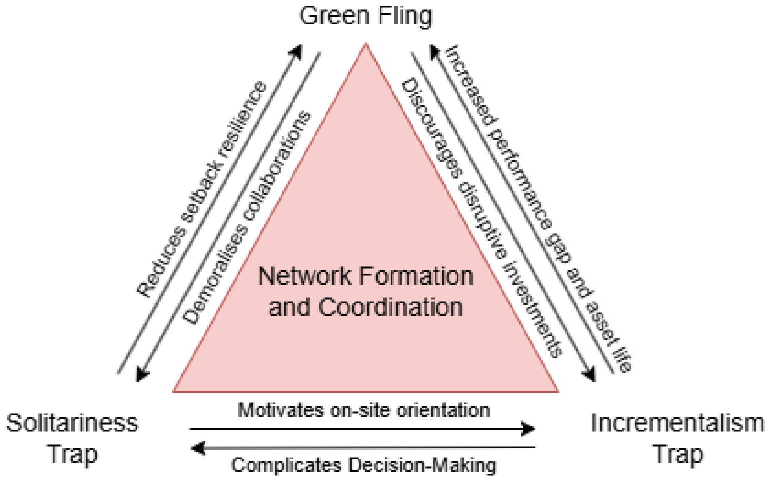

Figure 30: Triangular interconnection between the three self-reinforcing mechanisms, mutually hampering the *network formation and coordination* building block.

6.4 Conclusion

This section sets out to describe how industry dynamics and self-reinforcing mechanisms shape the decarbonisation prospects of the petrochemical cluster in the Port of Rotterdam. Through semi-structured interviews, the *Paradoxical Interdependence* cluster dynamic was identified. The cluster is characterised by physical interconnection without a social contract, resulting in strategic fragmentation. Through dissection of the dynamics, three self-reinforcing mechanisms are found that either cling on to the status-quo, or inhibit the development decarbonising alternatives. An overview of the mechanisms is given in Table 11. Combined, these identified mechanisms funnel resources towards individual incremental optimisation, whilst demoralising and constraining radical, low-carbon hydrogen-centric collaborations.

Table 11: Overview of self-reinforcing mechanisms present in the petrochemical cluster in the Port of Rotterdam.

Self-reinforcing mechanism	**Description**	**Lock-in**
Green Flings	Volatile fluctuations in energy-transition regulations result in investment uncertainty and risk, eroding collective expectations and the technology's reputation, demoralising further investment .	Lock-out - loss of competitivess relative to decarbonising alternatives
Incrementalism Trap	Site-level incremental innovation generate short-term decarbonisation gains and market competitiveness but widen the gap to emerging alternatives, increasing switching costs and collaborative decision-making complexity, suppressing deep decarbonisation.	Technological and Coordination Lock-in
Solitariness Trap	Lack of a shared, long-term cluster strategy obstructs collaborative action whilst the resulting absence of collaboration prevents the vision from emerging.	Incumbent Anchoring

Translated to the Technological Innovation System framework, the cluster dynamics and self-reinforcing mechanisms inhibit one key building block from being developed: *Network formation and coordination*. Even though the focal product group 'low-carbon hydrogen' is well understood technically, and the future customer base is promising due to a large variety of potential applications.

The interconnectivity between the *network formation and coordination* building block, and the building blocks *innovation-specific institutions* and *complementary products and services* shows potential for a snowball effect; developing the network formation and coordination may lead to development of the connected building blocks. Having now diagnosed the systemic barriers present in the cluster, in section 7 the creation of new paths escaping these barriers and developing them by establishing new reinforcing cycles may accelerate the development of the desired, low-carbon hydrogen TIS.

7 Path Creation and Development

7.1 Introduction

In this chapter, the path creation and development part of the path theorem is focused on. This focus is visualised in Figure 31. The goal is to pinpoint path creation potential. Mindful deviations can be initiated to break the self-reinforcing mechanisms identified in subsection 6.3. The chosen point of leverage wherefrom mindful deviations are begun is selected in subsection 7.2. Simply deviating is not enough to bring permanent change. Through path development, how a new path can be supported is indicated. How new paths can be created and developed is then operationalised by exploring what actor-type play what role in the process. Finally, the mindful deviation proposals and their development methods are reflected upon. The question answered in this chapter is:

"How to create, and develop a new path in a system transition context?"

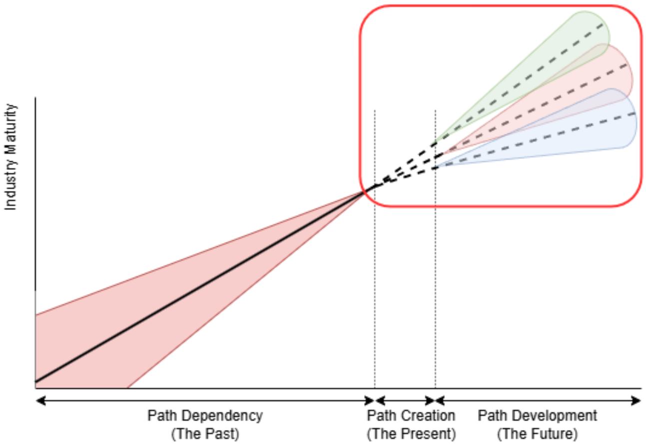

Figure 31: The path creation part of the path theorem focused on in the path creation- and development section.

In section 6, the paradoxical interdependence cluster dynamic has been analysed. From this cluster dynamic, three interconnected self-reinforcing mechanisms, present in the petrochemical cluster of PoR, have been identified in subsection 6.3. Together, these mechanisms inhibit the development of the *market formation and coordination* building block. Below, the three mechanisms are summarised.

- **Green Flings** - Volatile fluctuating policy regimes result in uncertain investment climates, affecting the success rate of low-carbon hydrogen projects, damaging the technology's network- and system resources. In turn, this lowers the technology's expectation, and signals this back to the *Innovation-specific institutions*, reorienting policy-making.
- **Solitariness Trap** - High-level governance of the established multinational firms result in long-term strategies being formulated outside the cluster. This vertical, top-down organisation results in a solitary, island-type of cluster.
- **Incrementalism Trap** - The high-level governance structures of established multinational firms, coupled with challenging macro-economic conditions and an unappealing domestic investment climate, drive these firms to prioritize short-term gains in the cluster while implementing innovative projects elsewhere. This focus often leads to missed opportunities and increasingly high switching costs over time.

7.2 Mindful Deviation

As the incumbent TIS is declining due to factors explain in in section 5, incumbent companies have enabled survival mode, solely focusing on short-term, incremental development. With the existing TIS eroding and the desired TIS still immature, shrouded in risk and uncertainty, the industry is paralysed. In both Technology Innovation Systems, the *Innovation-specific institutions* play the most significant role steering the current situation (P1)(P2)(P3)(P4)(P5).

However, this research focuses on the company perspective. The *Innovation- specific institutions* building block is only indirectly influenced by companies. To adhere to the research' approach, the *Network formation and coordination* building block is selected instead. Developing this building block would indirectly influence the *Innovation-specific institutions* building block by breaking away from the Green-Fling mechanism. Together with the connected *Complementary products and services* building block, formation of a coordinated network has the potential to overcome multiple barriers at once. Overcoming these barriers will accelerate the development of the desired TIS.

The *Market formation and coordination* building block faces systemic barriers due to the paradoxical interdependence cluster dynamic active in the cluster. The building block possesses great base potential which can be developed however: The cluster's actors possess a large amount of technology know-how, with research institutes (TUDelft, ISPT, Erasmus University) and innovative hubs (Up!Rotterdam, Rotterdam Partners, WeTech) complementing the innovative capabilities. Additionally, market players are increasingly more aware of the importance and benefits that collaborative initiative have, highlighting a dynamic pivot (P2)(P3)(P4) (Deltalinqs and KHengineering, 2024).

Whilst the awareness surrounding the importance of collaborative action is fairly present, the tendency to look on-site prevails. Energy-transition projects are characterised by large capital costs and uncertainty; Shell's Holland Hydrogen One cost over 1 billion euro to construct, whilst facing volatile regulation changes overtime. Furthermore, projects of this magnitude have been handled only rarely by most firms (P5). The majority of these projects require large-scale, multi-stakeholder collaboration for generating the required capital and mitigating risk (Zulkefly and Le Goazigo, 2024).

Due to the current focus on short-term gains due to harsh market conditions and the volatile policy environment, collaborative actions are rare. With the *incrementalism trap* mechanism (Figure 27) further adding complexity to the decision-making, and the *green fling* mechanism (Figure 25) slowly locking out the low-carbon hydrogen technologies, breaking the cycle is vital to enable the development of the desired TIS.

Applying (social) glue to the fragmented cluster is the first step necessary towards overcoming the systemic barriers, and accelerating the transformation of the cluster. The successful formation of a collective vision could decide the chicken and egg dilemma of the solitariness trap (Janipour et al., 2022), and enable bridging the gap between the existing system and desired system.

7.2.1 Cluster Billboarding

The solution to the solitariness trap proposed by Janipour et al. (2022) is difficult to implement in this study's case; Creating a shared cluster strategy for deep decarbonisation is difficult when the respective long-term strategy of the companies is made outside of the cluster. To attract multinationals towards the cluster and decide to implement their innovation projects necessitates an investment climate which motivates to do so. The national institutions responsible for policy-making are the main actor in creating a stable, attractive investment climate (P1)(P2)(P3)(P4)(P5)(Farla et al., 2012).

The cluster's facilitating authority, in this case the Port of Rotterdam, could however have a regional influence. By billboarding (advertising) their desired vision for low-carbon hydrogen related innovative initiatives, the facilitatory strength of the cluster can be applied to smoothen bureaucratic procedures, accelerating the establishing of newly entering actors accepting the invitation for low-carbon hydrogen innovation. P1 and P4 state that new market entries have been more common due to the emerging markets that the energy transition brings. The neutral positioning of the authority in terms of competitiveness within the cluster assists in creating networks and setting up collaborations (P3); They have the ability to mediate the corporate objectives towards the public climate goal.

P3 states that due to the energy-transition, a shift of power between actors within the cluster may happen if low carbon hydrogen is to become the dominant decarbonisation option. Industrial gas providing actors such as Air Products and Air Liquid are incumbent experts, possessing a vast understanding on hydrogen and already possessing dedicated infrastructure. These complementary and service-oriented firms already provide a strong foundational potential and can play a key role in accelerating network formation.

Path Development

The formation of a shared cluster strategy enables a positive self-reinforcing mechanism based on network effects; By successfully attracting vision-aligned actors towards the cluster, organisational resources are invested. Collaborations between the port's authority and incumbent service providers generate network resources. These network resources, in turn, increase the potential and value of the cluster, again attracting new entrants.

Successful cluster billboarding can lead to the development of network resources such as network reputation and network governance, developing the *Network formation and coordination* building block. As these network resources continue to pool, network effects will enable increasing returns to adoption, creating a self-reinforcing mechanism that develops the ecosystem of the desired TIS. In Figure 32, the path development loop is shown.

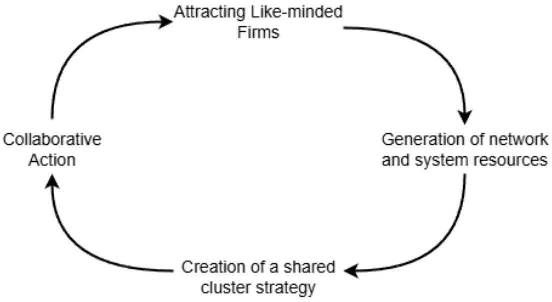

Figure 32: The self-reinforcing mechanism loop of the Cluster Billboarding

Resources

Cluster Billboarding is focused on generating social capital; The cluster authority advertising a long-term vision attracts like-minded actors to the cluster. This establishes network governance and collaborative platforms. The incumbent organisational resources such as technological know-how, infrastructure, and the Port's reputation offer a solid base for path creation and its development (Onufrey and Bergek, 2015). Successful collaborative initiatives positively influence the network reputation, whilst realising collective expectations, improving the technology reputation and legitimacy.

Developing the *network formation and coordination* building block requires, but also generates network resources and system resources. Network resources originate from pooled resources in collaborations between multiple organisations that develop the desired TIS in some way. System resources are generated by larger networks, or inter-network collaborations that share a strategy and vision, creating legitimacy of the desired TIS.

Operationalisation

Cluster billboarding requires the facilitating actor-type to embrace a dominant leadership role. In this case, the main actor is the Port of Rotterdam Authority. The port authority should start off by publishing a concise hydrogen-hub value proposition, inviting market actors that have overlapping agenda's with the hydrogen hub vision.

Actors such industrial gas providers (Air Liquide and Air Products), tankterminal operators (Vopak) and distribution operators (Gasunie) are potential first-tier partners. These actor-types are forecast to increase in market power as low-carbon hydrogen gains traction (P3). The willingness to collaborate towards the vision is thus assumed to be high. The involvement of these providing actor types create the base hydrogen hub task-force.

In this task-force, the port authority is responsible for smoothening permits for hydrogen-related activity in the cluster. Additionally, stewardship is included in the port's role. Promoting and incentivising a specific vision can enable hype-cycles, inflating the collective expectations. Continuous monitoring of the hydrogen hub is necessary to maintain control of the expectations. To monitor, the task-force should set up a key performance indicator (KPI) dashboard (workforce size, hydrogen-related FID status, sentiment of industry-related press) (Zulkefly and Le Goazigo, 2024).

Another short-term action is the incorporation of knowledge institutes into the billboarding activities. By emphasising low-carbon hydrogen in (applied) university courses and projects, the hydrogen-skilled workforce available is strengthened. Additionally, the knowledge institutes, together with the task force, advice the new, and incumbent producers on small scale hydrogen implementation projects, promoting the use.

On the long term, more iterative processes are carried out. The port authority focuses on governance, monitoring the KPI dashboard and continue to smoothen permit request processes. The growth of the hydrogen hub results in the access to higher-level resources, increasing the influence on regulatory bodies. Complementary product and service providers continue to develop the infrastructure. Additionally, together with knowledge institutes, utilisation systems are researched and developed to maintain the hub's innovative and progressing characteristic. Furthermore, the collaboration with new, and incumbent producers is intensified to start large-scale hydrogen projects that focus on demonstrating and enabling economies of scale.

Path Reflection

The formation of a coordinated network through Cluster billboarding is already visible in the Port of Rotterdam. A shared narrative is present between a variety of governing authorities, attempting to map, and legitimise the hydrogen trajectory. For example, the slogan: ”In Rotterdam we build the new economy” is circulated by Deltalinqs (2024), framing the Port of Rotterdam as the energy hub of the future, overlapping with PoR's ”Europe's Hydrogen Hub” (Port of Rotterdam, 2020).

One of the flagship projects up until now has been Shell's Holland Hydrogen One electrolyser. The project has needed to navigate many policy-changes and other challenges threatening the economical feasibility during the development. The industry has monitored the development process, and it has increased the reluctancy to invest (P1)(P5). P5 further states that the project is seen more as a proof-of-concept than an actual practical solution by the industry. Besides the successful delivery of a project, the smoothness of the development phase is also important. This is, again, significantly influenced by the regulatory landscape.

It is also important to remain critical on the credibility of the narrative. If the billboarding promises more than the cluster can deliver, it will have averse effects. P3 and P4 state that initially, an aggressive green energy push was seen, investing in off-shore wind parks, and claiming land for electrolyser projects. This was an overly optimistic push, as the technological, and regulatory challenges were underestimated. The narrative's credibility must be evaluated to diagnose if the billboard loop is still healthy, and not inflating into a hype curve. The KPI's proposed in the prior section will constrain this hype curve.

7.2.2 Industry-Authored Roadmap

In chapter Figure 24, the *green fling* self-reinforcing mechanism has been described. This mechanism is caused by the interconnection between the *Innovation-specific institutions* and *Network formation and coordination* building blocks. To break this mechanism, a plan to develop one, or both of the building blocks must be initiated. Since this study emphasizes the company perspective, *network formation and coordination* serves as the primary building block that the company can most readily influence.

Whilst there is a high level of system integration within the industry cluster, the strategic visions of the companies operating within the cluster is fragmented. Each company is looking at it's own business cases rather than undertaking collaborative action (P1)(P3)(P5).

In the *green fling* mechanism visualised in Figure 25, the uncertainty from, and towards the innovation-specific institutions enable the deterioration of the system resources collected by low-carbon hydrogen technology, which 'bleeds' the TIS' capabilities of large-scale transition.

Current roadmaps are top-down oriented, envisioning long-term possibilities to solve the decarbonisation puzzle of sector. The numerous roadmaps all state different outlooks on how the puzzle should be solved, indicating a fragmented coordination attempt. The positive of these roadmaps is the iterative improvement in understanding of the challenges and solutions overtime (P2). This fragmented characteristic is meant to decrease as the iterations are made overtime as the amount of uncertainties surrounding the emerging technologies decrease.

Industry-authored roadmaps, in turn, would allow for a better understanding of the industry's needs and the challenges they experience. This understanding can have a positive impact on multiple influencing conditions and building blocks. The envisioned positives are listed below.

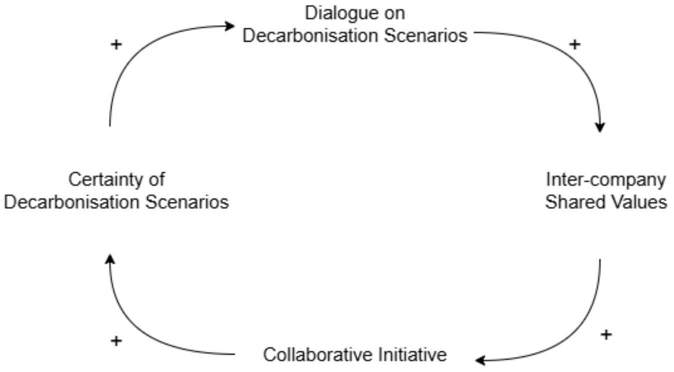

Figure 33: Industry-Authored Road Map Deviation

1. **Improved discussion on the possibilities within the cluster limits** - The dialogue leading up to the bottom-up roadmap, along with discussions about the strategies to achieve set goals, helps aligning the companies towards a shared vision. This alignment generates system resources such as collective expectations and technology dynamics, ultimately developing the *network formation and coordination* building block.
2. **Interaction of company dynamics** - The early phase of roadmap development allows for interaction between company dynamics. This level of networking explores potential collaborations and like-mindedness on the topic at hand, potentially reducing future decision-making complexity. Indirectly, this improves the *network formation and coordination* building block, as the *socio-cultural aspects* influencing condition.
3. **Improved communication to innovation-specific institutions and broader societal groups** - A unified industry vision, grounded in the real-world insights of insiders, signals an openness to change and is reinforced by tangible, actionable ideas. A bottom-up roadmap could

play a critical role in bridging the disconnect between policymakers and the industry. Furthermore, it could help dismantle the industry's reputation for unwillingness to change (P2) and its frequent scapegoating as the root of systemic, societal problems. This improved communication allows the innovation-specific institutions to better tailor future policies toward actionable ideas, improving the connected building block. Additionally, the *socio-cultural aspects* influencing condition is also positively influenced.

Path Development

Path development can only begin after the first roadmap is published. Especially when creating the first version it is thus essential to keep engagement high, and focus on acquiring momentum. Creating a bottom-up (historic) narrative of how the energy transition has begun in the cluster, the events that have happened, milestones that have been reached and so on create the engagement needed for parties to want to engage and contribute to the project.

Similar to the iterative nature of top-down roadmaps, the industry-authored roadmap is revised frequently overtime. By organising these revisions, discussion continues to be initiated, creating collaboration potential. Similarly to Cluster Billboarding, network effects overtime accelerate the market formation and coordination. Is it important to implement scaling loops, banking on successful pilots, to reduce uncertainties of similar and/or connected projects.

The path has to codevelop with the still fluctuating regulatory landscape. An adaptation loop, such as a project ranking and sequencing system embedded in the roadmap design, allows for flexibility in the project pipeline. This flexibility reduces the effects of the green fling cycle.

Operationalisation

Similarly to the Cluster Billboarding proposal, the facilitating Port of Rotterdam authority is the neutral, convening role with the first initiative. Contrary to the billboarding which attracts like-minded actors, the Bottom-up Roadmap focuses on coordinating the incumbent actors instead. The short term goal is to publish a first edition of the roadmap, showcasing different narratives to better expand on the problems experienced by the industry actors. The first initiative of the authority is to create alignment with the industry association, Deltalinqs. Having established a aligned problem focus and goal, industry players need to be invited to take part in the roadmap writing. Additionally, in the set-up of author assembly, the authority needs to create a NDA-compliant 'data room' to circumvent antitrust issues in the collaborative processes.

To keep the industry actors as the main authors of the roadmap, the industry association should govern the writing process of the first roadmap. The writing process starts off with further alignment and scoping of the main problem focus, analysing the challenges of the total industry cluster, but also per actor type. This is done through discussion groups. The outcome of the first roadmap is a 'truth-telling' narrative, showcasing the situation from the industry's point of view. Each actor-type established in the industry described its own situation which adds onto the main problem. Knowledge institutes complement this process by providing scenario tools and analysing potential solutions to parts of the formulated problem, closing the gap between the regulatory bodies and industry.

After the first edition of the roadmap is published, the long-term goal is enabled. The long-term goal is to close the gap between the industry and the regulatory bodies. The first step is to invite innovation-specific institutions to the discussion group in an attempt to uncover solvable aspects within the formulated problem. After, the iterative process of updating the roadmap through progress statements and lessons learned reduces the uncertainties present, and allows for new dialogue with regulatory bodies.

Path Reflection

P4 states that currently, the roadmaps are formulated under heavy influence from the industry. Invitations for discussion groups and interviews are received regularly. This way, the current published roadmaps already have a strong bottom-up perspective incorporated in them. It is, however, important to take into account what the main goal is of each roadmap. The reaching climate agreement goals is inherently a public goal, from which regulations and policies originate to make it a corporate goal too.

The authoring of such a roadmap needs a governing body to coordinate the roadmap, and keep companies engaged. The gap between the high-level directive and the local operational entities of the multinationals could generate misinformation if the high-level directives are not sufficiently engaged. As there is already an excess of roadmaps (P2)(P4), it is important to treat this roadmap as the single source of truth.

Additionally, the governing is important to refrain the incrementalism trap from enabling into the roadmap. The roadmap can stray into a focus on energy-efficiency tweaks, pushing out the more radical routes which intended. Lastly, the antitrust laws are also needed to be circumvented to allow for effective discussions and knowledge transfer. Some kind of pre-competitive contract of engagement is to be designed to do so.

7.3 Conclusion

In this section, the goal is to find out how path creation can be used to break away from the industry dynamics favouring the status-quo, and blocking the development of the desired TIS. Using the self-reinforcing mechanisms identified in subsubsection 3.2.1, the building block *Network formation and coordination* was selected as point of leverage to begin mindfully deviating from. Two path creation propositions have been formulated.

Cluster billboarding refers to advertising the ambition and vision of the port to become a hydrogen hub, and attracting like-minded entrants. Successfully attracting these entrants and facilitating smooth establishment of local operations generates network resources, which are necessary for collaborative initiative. Accumulated success improves the network reputation and collective expectations, enabling returns to adoption. If managed transparently and monitored with, for example, KPI's, the fragmented nature of the industry can be restored, counteracting the self-reinforcing mechanisms present.

The Industry-Authored Roadmap creates a platform for formulating a bottom-up narrative on the energy transition in the cluster. The iterative discussions and co-creation lead to a more coordinated network. Additionally, publishing these roadmaps assist in closing the gap between the industry and regulatory bodies, possibly resulting in better tailored policy-making. The over-time stabilisation of the regulatory landscape will counteract the green fling mechanism, whilst the formation of a coordinated network uncover collaborative opportunities, counteracting the incrementalism and solitariness trap.

The two path creation proposals demonstrate how new path trajectories can be orchestrated. By identifying and selecting a strong point of leverage, a multitude of barriers can be overcome. For the *Network formation and coordination* building block, an outward-oriented, confidence-building signal, and an inward-oriented, learning intensive coordination process is proposed. These initiatives highlight that strategic agency is essential for developing the Technology Innovation System.

It must, however, be stated that the regulatory landscape remains the decisive factor for making or breaking the cluster's energy transition. The building block was not selected as the leverage point due to the poor manipulate-ability companies have on the *Innovation-specific institution* building block.

8 Conclusion

This thesis set out to explore how the system transition from a fossil-based system to a hydrogen-based system can be supported from a company's perspective. It is specifically aimed at situations in which companies are embedded extensively within a large industrial cluster, discouraging individual radical changes. The main research question to be answered in this research is:

"How can companies organise for path creation, and drive its development in the petrochemical industry under a transitioning environment towards low carbon hydrogen?"

By (re-)defining and synthesising the Technology Innovation System Framework with the Path Theories (path dependency, creation and development), this research attempts to approach this challenge in a non-conventional way. The selected case study on the petrochemical industry sector in the Port of Rotterdam, the research attempts to bridge the gap between theoretical findings and practical application. Through an iterative combination of literature research and semi-structured interviews with relevant actors, the results were validated and reflected upon.

The results reveal that the current dominant Technology Innovation System is eroding due to an increasingly challenging macro-economic and regulatory landscape; The focal cluster can not compete on the traditional markets with the modern production facilities built abroad whilst navigating the ambitious domestic energy-transition policies discouraging the status-quo. The decline of the incumbent TIS could accelerate due to the closing of production facilities, disrupting the physical interconnections and reduce the economies of scale present.

The incumbent TIS breaking down does not however directly translate to the building up of the desired Technology Innovation System; there are too many uncertainties and risks present to enable large-scale diffusion of low-carbon hydrogen. The regulatory landscape, whilst encouraging the energy transition, is experiencing volatile fluctuations and is complex to navigate, discouraging the overall development of the TIS. The necessary infrastructure is also not yet in place to enable large-scale adoption of the product. The analysis concludes that there is still a gap to be bridged to enable the transition from the incumbent system to the desired system.

Through the scope of Path Dependency, industry dynamics explaining the challenges of the TIS-development have been identified. Paradoxical Interdependence caused by a physical interconnection, without social capital, majorly affects the formation and coordination of networks. Self-reinforcing mechanisms (Green Fling, Solitariness Trap and Incrementalism Trap) have been identified, helping to explain how this industry dynamic affects network formation and coordination, resulting in a triangular interconnection.

This identified interconnectivity also translates into the TIS, connecting the *network formation and coordination* building block with the *Innovation-specific institutions* and *Complementary products and services*. Breaking the self-reinforcing mechanisms preventing the development of the *Network formation and coordination* building block thus indirectly assists in the development of the mentioned building blocks, accelerating the overall development of the desired TIS. This translation signifies the compatibility of TIS and Path Dependency, generating the synergy benefits of diagnostic and dynamic capabilities. It also contributes to a more empirical way of approaching path dependency.

This study finally proposes path creation initiatives to break away from the identified self-reinforcing mechanisms, and develop a path that improves the network formation and coordination building block. The key factor from a company perspective is the collaborative action between actors. Two path concepts have been proposed: Cluster Billboarding attempts to attract like-minded actors towards the cluster by advertising and incentivising the desire for low-carbon hydrogen. Forming a network with these incoming actors allow for aligned collaborative initiatives, and can enable further development through network effects within the ecosystem. The Industry-Authored Roadmap aligns authors' visions, uncovering what how low-carbon hydrogen can play a realistic role in the energy transition. This roadmap also helps in closing the gap between regulatory bodies and the industry, better translating the needs of the incumbent actors. Overtime iterations combined with successful collaborative initiatives generate technology reputation and social capital, enabling path development.

This research has highlighted that the transition challenge is more so an organisational, and regulatory challenge rather than a technological one. Awareness for the agency companies can have is generated, proposing potential pathways to formate a coordinated network from a bottom-up perspective.

9 Discussion

9.1 Practical Relevance

The research highlights the incredibly challenging state which the industry is in; forced to leave their status-quo, without a new system to move to. This tension has already eroded the cluster's competitiveness, and threatens further plant closures. The closures, in turn, affect the economies of scale generated by the cluster's system integration, thus further eroding the cluster's competitiveness. In this study, self-reinforcing mechanisms are uncovered which help explain why this squeeze from two sides is present. Firms are locked into site-level optimisation, and the cluster lacks a coordinated market formation.

The practical relevance of this study lies in showcasing how these mechanisms inhibit the development of the new system, and proposing path deviations to escape them. The necessity of market formation and coordination within the cluster to further develop a low-carbon hydrogen system is highlighted; The required investments possess large amounts of techno-economical uncertainty and are capital intensive. Collaborations help mitigate the risk, whilst benefiting from the knowledge of each of the collaborating parties. Taken as the point of leverage for path creation, two deviations are proposed:

- Cluster Billboarding - An outward signal that Rotterdam is Europe's hydrogen hub, backed by an attractive ecosystem with significant facilitatory strength. Like-minded industry entrants create the necessary market coordination and positive network effects needed for further development.
- Industry-Authored Roadmap - An inward-oriented initiative owned by the industry to align the visions within the industry, and close the gap between the industry and regulators.

Improved market formation and coordination also generates network- and system level resources, necessary for the continuous development of the industry towards low carbon hydrogen. Technology legitimacy and reputation, as well as the increasing return of adoption strengthen the technology system over time.

This study also incorporates the forecast shift of market power towards complementary service-providing actors into the proposed deviations. The established knowledge and infrastructure industrial gas providers have focused on hydrogen create significant facilitatory strength in the transition. The actors providing complementary products and services provide the basis for development of the low carbon hydrogen system. The collaboration between the governing port authority and this actor group has strong potential to kickstart further development.

By reframing the transition challenge from a top-down perspective to a bottom-up perspective, this study equips companies with the agency of strategic initiative, steering the cluster towards a competitive low-carbon hydrogen system.

9.2 Scientific Contributions

9.2.1 Theoretical Contribution

The research is conducted through a methodology framework which synthesises the TIS-framework and the Path theories. The results signify the additional value created by this synergy. It enables an empirical base which path dependency and creation lacked (Vergne and Durand, 2010). Additionally, the building blocks and influencing conditions featured in the TIS-framework assist in the systematic identification of self-reinforcing mechanisms.

The path theories, on the other hand, enhance the TIS-framework by implementing dynamic characteristics into the relatively static, diagnostic framework. The influencing conditions allow for a peek into the temporal stability and status of a building block, but doesn't further describe what kind of influence this is. The lock-in sources, self-reinforcing mechanisms and lock-in types are a great addition to the framework in that sense. These self-reinforcing mechanics also lead to uncovering intra building block feedback loops. These feedback loops may help understand why TIS development stagnate even when majority of the building blocks show mediocre performance.

Substituting the TIS' original 'resources' influencing condition by the level-based resources of Farla et al. has contributed to describing the system-level scope of the case study (Farla et al., 2012). The original resources influencing condition lacked explanatory strength outside the company level. Whilst deviating from this level did result in more global proposition making, lacking operation-ability, it does better explain as to why collaborations and networks are a key factor in the transition; The incorporated resource-levels make the essential 'tacit' resources more visible.

In the TIS framework that is part of the foundation of this research, future research towards company strategies that can influence building block build-up is stated to be of interest (Ortt and Kamp, 2022). This research has extracted value by exploring this research path. The research describes the diffusion pattern of low carbon hydrogen in the hard-to-abate petrochemical industry. Whilst the technology is already introduced, further diffusion during the adaptation phase is hampered. Ortt and Kamp's research mention several examples of strategy types which might help overcoming the barriers. These examples are identified during this research. The given examples of lobbying and networking type strategies align with this study's conclusions and propositions.

Continuing on the forecast valuable research inquiries proposed by Ortt and Kamp, the interaction between building blocks and influencing conditions have been identified. By implementing path dependency, a dynamic view of the TIS was uncovered. This revelation enhances the explanatory power of TIS change, and improves the understanding of the TIS' status. Incorporation of the self-reinforcing mechanisms proved to be a compatible suitor to enable the analysis of TIS dynamics. By reconceptualising niche strategies towards path creation's mindful deviations, the TIS framework is now also better suited to tackle wicked problems. In these types of problems, such as the hard-to-abate industries, the uncertainties and volatility does not allow for straightforward strategy formulating. Whilst path creation, as implemented in this study, still lacks concrete operationability, it has created an understanding of the situation, whilst identifying key leverage points for path development.

9.2.2 Methodological Contribution

In this study, an iterative-learning approach has been applied. By analysing the TIS status and conducting the interviews in a parallel fashion, the two courses of action complement one another. This mutualism resulted in an enhanced nuanced perspective in the TIS analysis, whilst creating a flourishing interview environment through strong, directed guided questioning. Additionally, the interviews had a double function, generating more insight regarding the TIS' status and validating or correcting prior done analyses.

9.3 Assumptions and Limitations

9.3.1 Generalisability

The selection of one hard-to-abate, cluster as a case study, a mixture of qualitative data collection method and the selection of a single product group (LCH2) limit the generalisability significantly. Applying this study's methodology and conceptual framework to other cases in which the dynamics between actors and governing bodies may differ is likely to result in other outcomes.

The qualitative data triangulation between mainly European grey literature and five semi-structured interviews further limit the generalisability of the results. Five interviews do not suffice past the use towards an exploratory goal as is done in this research. Conducting more interviews will help increase the nuances, and allow for the reaching of a more explanatory goal.

The focus on low carbon hydrogen as a product group overlooks technological interplay between emerging alternatives such as electrification, bio-feedstocks, and CCUS. This limits the depth of the Green Fling mechanism for example; hydrogen is now compared to 'emerging alternatives', resulting in the inability to compare defined technology groups. Technological (in)compatibility is defined as a lock-in source, constraining future decision-making flexibility of the cluster when adopting one of these technologies early (Janipour et al., 2020).

At the time of writing this research, the world is in a volatile state. Many conflicts are seen worldwide, generating significant geopolitical events. With energy, and oil and gas specifically, playing a major role in geopolitics, changes may happen faster than the empirical window has captured in this research. This has consequences for the validity of the empirical analyses, and the conclusions and recommendations derived therefrom.

9.3.2 Limitations

Path Theories

The path theories have been used selectively throughout the research. The contingent nature of path dependence, referring to unpredictable events that influence the path's trajectory, have not been actively analysed. The historical aspect is only seen in this study when the paradoxical interdependence dynamic was identified; The multinationals deciding to establish themselves in the PoR was not due to existing cluster benefits, but due to the strategically strong position of the harbour. A more structured interview approach purposed towards historical analysis would complement the research as to *why* previous initiatives succeeded or failed, and what decisions were made under what circumstances.

Scope of Identified Self-Reinforcing Mechanisms and Leverage Points

The research followed a hourglass-type of build-up; A convergence towards a single point of leverage is made (network formation and coordination building block), after which the research diverges into two different path creation initiatives. The identified self-reinforcing mechanisms, points of leverage, and path creation initiatives presented are, however, non-exhaustive. more self-reinforcing mechanisms are very likely to exist, and interact within the dynamics of the cluster. For example, the short-termism trap, formulated by Janipour et al., has not been taken into account as the interviews did not mention any of the aspects of the mechanism (2022). It is likely that this self-reinforcing mechanism is present in the cluster due to the amount of publicly listed companies.

An enlarged bandwidth of mechanisms brings forth different mechanism interconnections, creating more leverage points from which path creation can be initiated. Additionally, these new interactions can change the triangular interconnection surrounding the network formation and coordination building block positively and/or negatively.

However, in this study extracted some of the key dynamics by using the iterative-learning methodology. The iterative process between TIS-analysis and semi-structured interviews that enhanced the direction of the study. Points of interest derived from the first interview were formulated into questions for further inquiry in another interview. This resulted in either a validating answer with an expanded context, or a new perspective on the topic. The line of inquiry involving market formation and coordination penetrated all five interviews with an overlapping perception on collaborative necessity; Complementing companies' core competencies, and risk mitigation have frequently been mentioned (P2)(P3)(P4)(P5). So whilst there are certainly other mechanisms present, the found triangular interconnection is argued to be a robust one.

TIS scoping method

The scoping step of the TIS-framework was also substituted by the scoping method of Bergek (2015). Originating from the structural components of Malerba (2002): (1) Technology, (2) Network of actors, (3) Supporting institutions and (4) Demand. This was substituted by the three points of choice, selecting: (1) Focusing device, (2) Breadth and depth, (3) Spatial domain. This scoping method, similar to the level-based resources, is more applicable to the analysis of a system-level scope. Again, similarly to the resource substitution, has caused a more global-scale analysis, lacking specific company names and their relations and dynamics.

Cross-sectoral analysis

Cross-sector transition has been stated to be an important aspect to take into account (Port of Rotterdam, 2024b) (Zhang et al., 2023). By solely scoping on the petrochemical sector, solutions such as cross-sectoral heat waste distribution have not been incorporated. Adjusting the scope of a sector towards a geographic regime would better incorporate the inter-sectoral interactions.

9.4 Future Research

The exploratory nature of the research has generated a variety of paths for further inquiry. Whilst currently it is assumed that all building blocks are equal, it is likely that the sensitivity and the weight factor of the individual building blocks is connected to the chosen scope of the TIS; in a low level scope it can be easier to vertically integrate complementary products and services and coordinated market formation. This is an interesting inquiry for future research, as it could generate insight on how much the performance of a specific building block inhibits the general development of the TIS.

Learning Effects

In this study, the contribution of the introduction of different level of resources is significant, as it better explains the cluster dynamics present. However, as shortly explored in section 9, different resource types can possibly have different influences on the self-reinforcing mechanisms. An inquiry towards how lessons-learned and trial-and-error generated knowledge influence the dynamics is of future interest to further expand the explanatory power surrounding these self-reinforcing mechanisms.

For example, in subsubsection 6.3.1, the aspect enabling the self-reinforcing vicious cycle is are the system resources *Collective Expectations* and *Technology reputation*. However, in a alternative approach one could argue that the generation of knowledge through lessons-learned and trial-and-error outpaces the deterioration of said system resources. Knowledge generated through these sources create more awareness and knowledge of the technology and its application in a variety of markets, resulting in more certainty around the technology group. This could ultimately boost the system resources instead of deteriorating them. Additionally, the translation of resource levels back to human, financial and natural resources is of interest to enhance the operation-ability of proposed path creation initiatives.

Expiration Date

Earlier in this chapter, the global volatile situation affect the timespan in which the findings of this research are valid. For example, the grey literature used in the TIS analyses and the current regulatory landscape can shift quickly. It is important to be able to forecast, and evaluate in what timespan the results are accurate, before expiration sets in.

The interviews state to have experienced a hype-cycle. An aggressive green energy push was seen, which slowed down as the both industry, as governments overestimated the role of various decarbonising technology routes (P3). A sobering pivot in strategy was introduced due to poor techno-economic feasibility, sobering the market (P3)(P4)(P5). This radical change, and sobering of the market has taken place over a timespan of around five years. If this study would have been conducted in the moment of hype, a completely different situation would have been evaluated.

The incumbent system's state of decline increases the instability present. This instability directly influences the durability of the research' results; short-term strategy dominates during times of hardship. How aspects such as the industry lifecycle stage, hype cycles and macro-economic volatility impact the durability of the results is an important future research topic.

Besides the expiration date of the framework, enhancing the adaptivity of the framework is also a valuable future inquiry. The energy transition goals are set to be completed in 2050. If a new episode would take place around every 5 years, many reviews would be necessary to keep the evaluation up to date. By further defining the influencing conditions, the stability evaluation can be enhanced.

Further Exploration

The study identified one industry dynamic, three self-reinforcing mechanisms, one point of leverage, and two path creation initiatives. These findings are however non-exhaustive. Future research to what other mechanisms affect the TIS could be a very valuable line of inquiry to formulate more strategies, accelerating the development of the desired system.

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A Appendix

A.1 Hydrogen roadmaps and strategies

Table 12: A non-exhaustive overview of the different roadmaps and strategies envisioned for a future hydrogen economy.

Roadmap/Strategy	2030 Vision	2050 Vision
Government Strategy on Hydrogen (RVO, 2020)	• **Electrolysis capacity:** 3-4 GW of green hydrogen production. • **Integration:** Hydrogen use in industry, transport, and heating. • **Infrastructure:** Develop pipelines and refueling stations.	• **CO2 Reduction:** 95% reduction compared to 1990. • **Market Development:** Fully developed hydrogen market supporting multiple sectors.
Outlines of a Hydrogen Roadmap (Gigler and Weeda, 2018)	• **Green Hydrogen Production:** 3-8 GW electrolysis capacity. • **Infrastructure Development:** Hydrogen transport and import/export network.	• **Expansion:** 13-45 GW electrolysis capacity. • **Hydrogen Transit Hub:** Export 50-150 TWh of hydrogen
Port of Rotterdam Hydrogen Vision(Port of Rotterdam, 2020)	• **Infrastructure Development:** Establish Rotterdam as a central hydrogen hub for Northwest Europe.	• **Supply:** Provide 3.2 million tonnes (MT) of hydrogen to maritime users. • **Demand:** Supply 20 MT of renewable and low-carbon hydrogen per year.

A.2 Features and Indicators of Paths

Table 13: Constitutive Features and Potential Indicators of Paths

Constitutive feature	**Definition**	**Indicators**
Level interrelatedness	A focal level of analysis that needs to be conceptualized in relation to surrounding levels of analyses that are more micro and macro.	Actors and/or observers relate their activities (1) recurrently, (2) intensively, (3) and to an important extent not only to a focal, but at the same time to more micro and macro levels of analysis.
Triggering event	Incident that potentially induces the current and/or future trajectory of a path.	Actors and/or observers assess an incident as being (1) decisive, (2) initiating self-reinforcing processes for an option's likelihood to be prevalent in the future...
Non-ergodic process	Course of simultaneous and/or sequential events that lead to an outcome, which is not automatically determined from the onset but is not arbitrary, either.	From the onset, (1) options of equal potential are (2) narrowed down to (3) a final solution.
Self-reinforcing processes	Course of interlocking simultaneous and/or sequential events that are progressively aligned to each other, thereby fostering the overall course of a path in an overall direction and potentially leading to a momentum; in this connection, certain initial conditions are connected with certain results.	Over time, (1) (interorganizational) overarching institutions that serve to formulate and pursue joint objectives are established, (2) the design and usage of complementary management systems with regard to organizational aspects, and operations, (3) learning effects reinforce...
Lock-in	Situation or outcome where the trajectory of a path becomes confined to a single solution that does not need to be efficient.	(1) investments are stable or increase with regard to the prevailing option, (2) investments in alternatives are reduced, (3) alternative options are considered to be niches...
Multiple actors	Constellations of individual or collective agents.	(1) number of actors (more than two), (2) properties of actors, (3) actors bound together by sets of relations...

A.3 Semi-Structured Interviews

A.3.1 Inquiry sequences per theme

The interviews are conducted via preferably in-person meetings, but video calls may be conducted depending on the participant's availability. All the interviews will be audio-recorded and transcribed for further data processing.

Every question sequence starts off with open, ambiguous questions. This way, data which might be of importance for the research, but wasn't yet extracted by the literature research can be caught. It also allows for a large amount of data to be collected, after which more focused questions can be asked. The open questions start off at the participant, after which the scope is widened to his/her respective organisation, and finally the industry cluster. For example:

- *How are you/your firm/your industry involved in the energy transition?*
- *What barriers keep you/your firm/your industry from contributing (more) to the energy transition?*

After these open question types, more specific and directed questions are asked concerning the contents of the literature research. The participant is asked to take a look at the (simplified) version of the TIS building blocks, and asked to gauge the status of each. The strongest, and weakest building blocks are asked to be elaborated upon. This is also requested for the building blocks which have been gauged differently through literature research.

Next, the barriers are further elaborated on. To refrain from using unknown jargon, lock-in has not been used. The barriers are navigated through by asking the participant to look at a (simplified) version of the lock-in sources. These can be connected to the answers to the open question above. To connect the lock-in source to the state of lock-in, the reinforcing mechanisms and industry dynamics enabling this are discussed with the participant. The theme is then concluded by tracing back the conversation, promoting the chance of establishing a new connection between path dependency factors.

As mentioned earlier, this sequence is done for every theme. The open, ambiguous questions are itemized below.

- *What are the drivers for you/your firm/your industry to contribute to the energy transition?*
- *How/when do you/your firm/your industry initiate a project driving the energy transition?*

After these open questions, the mobilisation of resources is discussed. Especially the type of resources that are important are looked for. What resources do you need for organisational, network, and systemic change? Then, the TIS building blocks are looked at again. The opinion about which building block is easiest to dismantle and easiest to develop and why. The industry dynamics and reinforcing mechanisms are then re-introduced to see if they are applicable for this development and/or dismantling. This theme is concluded by tracking back on the conversation, again promoting the chance of establishing a new connection between path creation and development factors.

The interview is then concluded, asking the participant for any remarks and comments and any last questions before finalising the session.

A.3.2 Human Research Ethics

In this research, interviews are used for data collection and validation of findings. Because this research method involves human research subjects, the research design must comply with the Human Research Ethics (HRE) guidelines. The three considerations of research design consist of minimising risk, risk-planning session and communicating & managing risk.

Research ethics focus on identifying and mitigating any undue harm or disproportionate risk. Potential damage to environment, animal suffering, security of freedom, and other harmful exposures to human volunteers are expected to be identified and mitigated. Incorporating research ethics into the research plan will result in more responsible and high-quality research. In this research, interviewing is the method applied which subjects participants to potential harm. The potential ethical implications are explored through the guidelines granted by the TUDelft.

The summaries are sent towards the respective participants for final consent of the data and its processed structure. The summary results are used to compare literature, and case study findings and validate and add upon the findings.

A.4 TIS-analysis Components

The description of the building blocks and influencing conditions defined by Ortt and Kamp have been adopted (Ortt and Kamp, 2022). The influencing condition *Resources* has been substituted by the resource levels to improve its applicability in the research context (Farla et al., 2012). The analysis steps are adjusted to better fit the path theorem.

Building Blocks

1. **Product performance and quality** - To be able to compete with existing products in the market, the new product should be able to sufficiently match the performance and quality. However, new products generally need some revision rounds to fix early version faults and errors.
2. **Product price** - Similarly to the first building block, the new product needs to achieve a price point capable of competing with the existing products on the market. Because of the direct and indirect costs related to the development and production of the new product, it remains a great challenge reaching a competitive price point early on.
3. **Production system** - Being able to deliver high quantities of high quality product is of importance to achieve a high adoption rate. Additionally, economies of scale results in the reduction of production price. This then results in the ability to lower the product price, improving the status of building block 2.
4. **Complementary products and services** - Building block referring to the availability of services and products which support development, production, distribution, and utilisation of the new product. A high amount of complementaries results in an increased product value as networks effects increase.
5. **Network formation and coordination** - The network formation consisting of upstream and downstream processes, complementary services and products, as well as other actors necessary to set-up a robust value chain. The coordination and formation of this network is key for the longevity of the product.
6. **Customers** - The identification of the customer segment that could benefit from the product is an important building block. When products are developed without including the potential consumers throughout the process, customer-related issues will damage the adoption rate. The customer's potential lack of awareness can also damage the rate of adoption, as the customer does not know they need the product, the product exists or about the product's functionality.
7. **Innovation-specific institutions** - Closely related to the institutions structure described in subsection 3.3, this building blocks refers to the formal and informal rules surrounding the innovation. Rules such as laws, standards and regulations can all support or block product development and adoption rate.

Influencing Conditions

1. **Knowledge and awareness of technology** - Encompasses both fundamental and applied technological knowledge. Fundamental knowledge consists of the base technological prin-

ciples found in building blocks such as product performance and quality, production systems and complementary products and services. Applied technology knowledge leans towards the competencies necessary to develop, improve, produce and repair components originating from the mentioned building blocks.

2. **Knowledge and awareness of application and market** - This condition refers to potential applications, knowledge of the market and the actors involved in these applications, This knowledge is required for all actors including customers to formulate strategies, and formulate tailored product requirements.

3. **Resources** - Refers to the organisational-, network- and system level resources, necessary for manipulating the company-, collaboration- and cluster level respectively (Farla et al., 2012). Organisational resources are created intra-company, and network resources inter-company. System-level resources are generated inter-network, enabling significant influence on large-scale transitions. A lack of network- and system level resources will hamper company-influence on the development of building blocks.

4. **Competition** - Refers to the competitiveness between incumbent technologies, and alternative emerging technologies. To enable adoption of the product, substituting the incumbent technology, it needs to have some kind of significant competitive advantage. Technological incompatibility may result in the requirement of new markets, supply chains and production systems, slowing down the formation of the Technology Innovation System.

5. **Macro-economic and strategic aspects** - Encompasses economic situations, such as recessions or economic growth, influencing the demand of a product for example. Strategic aspects refer to the interest in the product and its TIS on a (inter)national level. High interest influences the development of the TIS significantly.

6. **Socio-cultural aspects** - Refer to the norms and values within a socio-technical system. Whilst less formal than laws and rules, socio-cultural aspects can have a large influence on them. 'Traditional' methods, habits and values may become visible in interest groups or relevant stakeholder groups. It can thus have influence on the formation of different TIS building blocks.

7. **Accidents and event** - Refers to influences from both outside (wars, political turmoil and natural disasters), as inside the TIS (accidents with products or in production, emergence of new tech). Can have shock-type influence, or over a longer timespan.

TIS Analysis Process

Table 14: Steps and Sub-Steps in the Analysis Process, adopted from (Ortt and Kamp, 2022).

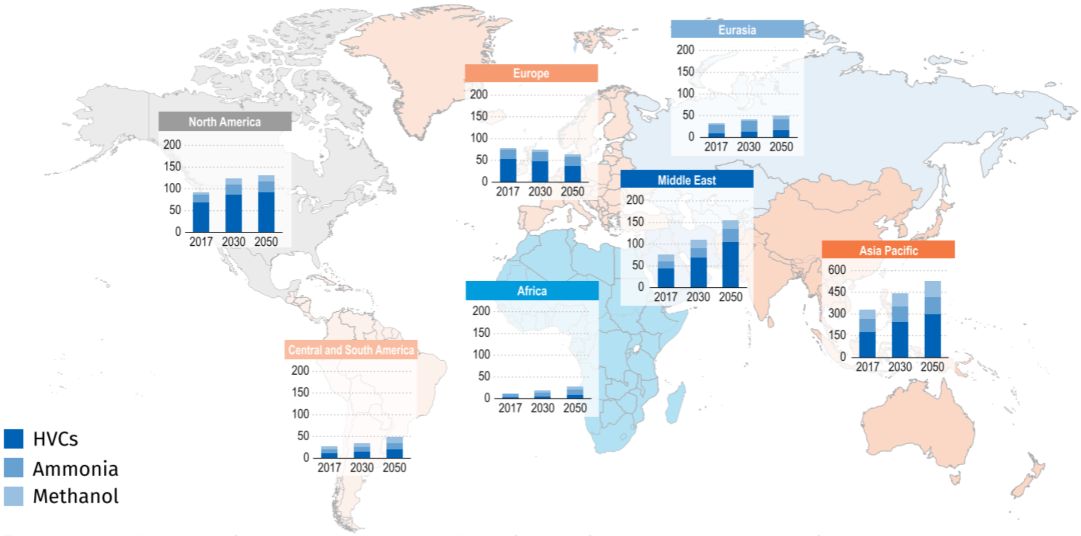
Step	Sub-Step	Description
1. Structuring the Analysis	a. Define the system boundaries	Identify the technological field, geographical scope and actors involved in the TIS.
	b. Map the system components	Categorize actors, networks and institutions that form the system.
2. Exploration of building blocks	a. Information gathering per building block	Use *different sources* to gauge the status of each building block.
	b. Status assessment of building blocks	Status of building block can consist of complete, partly complete, or missing. Partly complete, or missing building blocks may be the result of lock-ins, or other barriers.
3. Explore possible paths	a. What incumbent building blocks can be re-assembled?	Breaking through lock-ins, mobilizing the resources to transition towards the goal TIS.
	b. What building blocks can be created?	Describing how missing building blocks can be created using path creation and development.
4. Explore the status of the influencing conditions	a. Identify causes of incomplete building blocks	Further identify the lacking building blocks using the *7 influencing conditions*.
	b. Further specification of path creation/development	Describe the influence of momentum and agility on the path.

A.5 Decarbonisation options

Table 15: Technological decarbonisation options for the (petro)chemical sector (Oliveira and Schure, 2020)

Category	**Technology**	**Relevant to Process**
Carbon capture	Carbon capture and storage	Applicable mainly for hydrogen production, FCC, and gasification units. Possibly applicable to all current stacks, but limited by space requirements.
Fuel substitution	Electric furnaces	Possibly applicable to all processes that present gas-fired equipment (e.g., atmospheric distillation, cracking processes, reforming).
	Electric boilers	Steam boilers.
	Electric shaft equipment	Steam turbine replacement.
	Blue/green hydrogen as fuel	Possibly applicable to all processes that present gas-fired equipment (e.g., atmospheric distillation, cracking processes, reforming).
Feedstock substitution	Co-processing (5–10%) pyrolysis bio-oil from biomass in FCC unit	Co-feed for FCC.
	Blue/green hydrogen as feedstock for processes	All hydrotreating and hydrocracking processes.
Process design	Stand-alone plant for biofuels production via pyrolysis bio-oil upgrading	Process alternative for production of LPG, gasoline, kerosene, and gasoil/diesel.
	Biomass gasification and Fischer Tropsch for fuels production	Process alternative for production of LPG, gasoline, kerosene, and gasoil/diesel.
Residual heat usage	Use of process heat, internally or externally	All processes with excess heat.

A.6 Forecast Regional Production of Primary Chemicals



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Figure 34: Forecast distribution of primary chemical production (CEO, 2025)

A.7 Global Interview Process

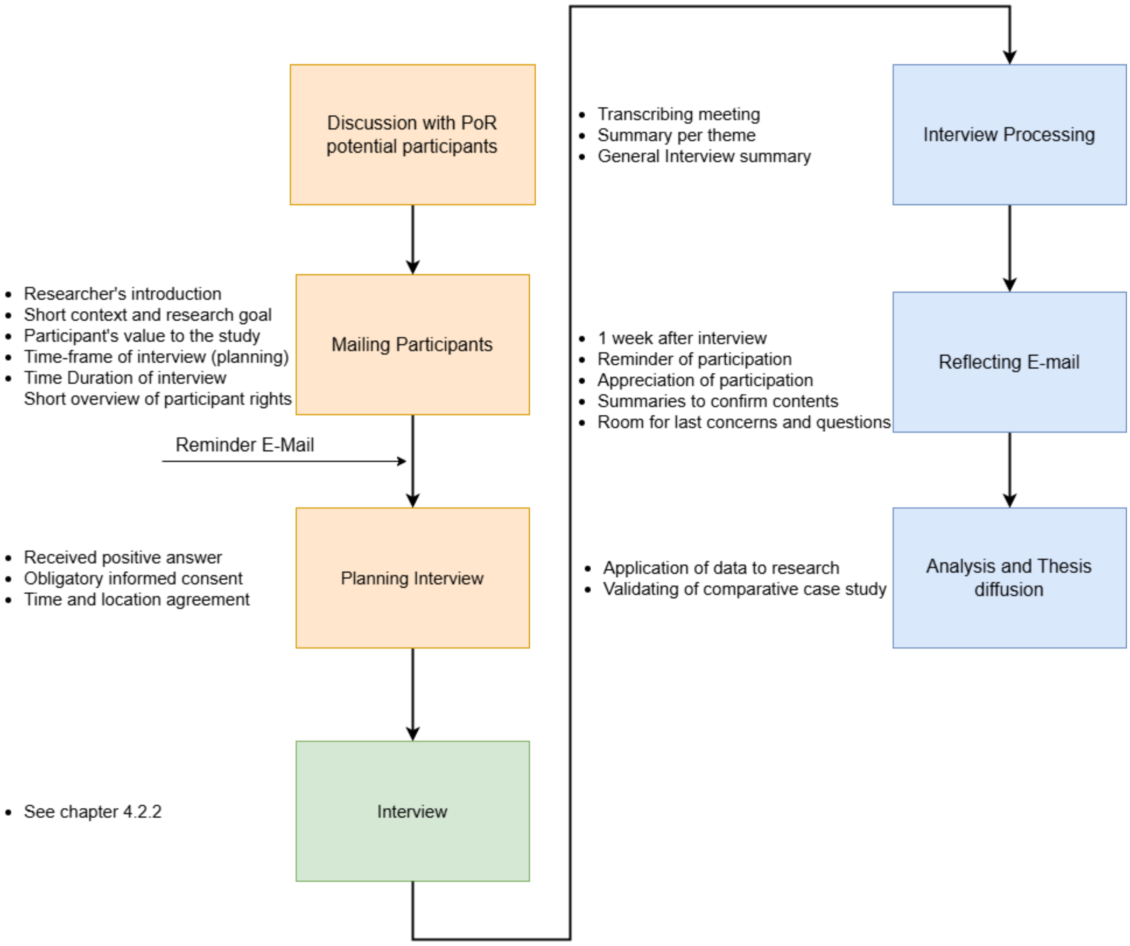


Figure 35: The global interview process. The orange blocks are preparation processes, the green block represents the actual interview. The blue blocks represent the data processing, and concluding processes.