Overcoming the barriers of electrifying Dutch light hydrocarbon cracking

A mission-specific innovation system analysis

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Abstract

The Light Hydrocarbon Cracking (LHC) industry needs to decarbonise its production process to achieve the nationally set mission for a carbon-neutral industrial heat system by 2050. The main solution to this mission is electrification of the cracking process, also known as e-cracking. E-cracking is currently in the pilot phase, with two active demonstration projects, but faster development is required should the deadline be met. This study, therefore, aimed to identify and analyse the barriers inhibiting this transition. The theoretic framework of the Mission-specific Innovation System (MIS) and the systemic problems from the Technological Innovation System (TIS) framework formed the base for this research. A modified MIS analysis was used to analyse the LHC industry.

This modified MIS approach takes a barrier-centric approach, where the system barriers are identified and qualitatively explored, before analysing them. Afterwards, the analysed barriers were related to the system functions, to serve as intervention points targeted recommendations could be aimed at. Expert interviews with actors from different parts of the system and desk research were used to identify the barriers. Seven central barriers emerged from the data. These were the incalculability of financial risk into the market price, the infeasible business case for e-cracking, uncertainty regarding grid expansions, insufficient communication channels, limited cooperation, and general uncertainty. The analysis revealed which problem types lay central in causing these barriers, and which MIS system functions lay central in solving them. The problem types that are most relevant to the barriers are primarily related to problems with institutions and interactions in the system, while system functions that played a particularly important role were knowledge diffusion, knowledge creation, and market formation. Keeping the discovered relationship between the barriers and the system functions in mind, targeted recommendations to alleviate the system barriers and thus improve the performance of the innovation system have been made in the conclusion. Recommendations include suggestions for protective and punitive policy to bolster the e-cracking market, a coordinating entity to facilitate interaction and collaboration in the system, a change to the industry mindset, and government investments to enable grid expansion for sustainable transitions.

This thesis contributes to the growing body of MIS literature. It takes a new barrier-centric approach and utilises the MIS in an incumbent, competitive-natured industry. Additionally, this thesis utilises the MIS in a system where primarily one technological solution is used to achieve the mission, bringing new insights to MIS dynamics.

Table of contents

1. Introduction

The environment has become the focal point of several societal problems. One of the world's most pressing issues is global warming. The summer of 2023 was the hottest summer on record to date, with global mean surface air temperatures reaching 16.77 °C for the first time, compared to 16.48 °C in 2019 (Copernicus, 2023). Furthermore, reports from the World Meteorological Organization (WMO) predict that, following current trends, global temperatures will break new records in the next five years (WMO, 2023). To prevent this, the European Union (EU) and its constituents have set up the mission to achieve a 55% reduction in greenhouse gas (GHG) emissions by 2030 and net-zero emissions by 2050 in the European Green Deal (EGD) (European Commission, 2019).

To comply with this, the Netherlands has set up its plan to become carbon-neutral by 2050. Paramount to the success of this plan, are the 'missions for the topsectors' set up by the Ministry of Economic Affairs and Climate (EZK) (EZK, 2019). These are five missions that have been created for the most influential industry sectors (top sectors) in the Netherlands to ensure the country's future is sustainable. Among the five missions is a mission to reach only net-zero products and processes across the Dutch top sectors and to have a CO_2 emission equivalent of 36 Mton by 2030. With this comes the sub-goal of having a CO2-free industrial heat system by 2050. This will be particularly difficult for chemistry industry. The chemistry industry is an essential part of the Dutch economy. It produces essential resources for other industries, making the chemistry industry a key player in the sustainable transition (Znidarsic, 2023). Currently, this industry relies on several high-temperature processes powered mainly by fossil fuels.

One of these high-temperature processes is Light Hydrocarbon Cracking (LHC), which is one of the most energy-intensive processes in the chemistry industry (Navigant, 2019). LHC refers to the chemical process where long (hydro)carbon chains, such as (bio-)naphtha or pyrolysis-oil, are broken down into smaller (hydro)carbon chains (olefins), like ethylene (Fakhroleslam & Sadrameli, 2020). These olefins form the basis for other important products, such as medicine and plastics. The cracking process happens in large furnaces under high temperatures currently achieved by burning fossil fuels. Some of these fuels are virgin fossil fuels, while some are supplied by the cracking process itself. Gasses are released as a by-product during the cracking process, which can be combusted in the furnace to produce additional heat. This makes the process somewhat self-sufficient. However, this process causes a lot of carbon emissions. In 2022, the global LHC industry is responsible for 366 MT of CO2 emissions (Tijani et al., 2022).

There are several options to decarbonise this process, including carbon capture and storage (CCS), hydrogen-fired furnaces, or electrification. The most prominent solution to decarbonise LHC in the EU is electrification, which involves switching to an **electronic cracking furnace (e-cracker)**. An e-cracker replaces the traditional fossil fuel-fired furnace with one powered by electricity (ISTP, n.d.). Thus removing the emissions from the heating process. In addition, using green electricity would make the entire production process emission-free. Combining this with sustainable feedstocks, like bio-oil or bio-naphtha, instead of the fossil hydrocarbons LHC currently uses, will allow the chemistry sector to make carbon-neutral materials for other industries. This makes the LHC industry key contributor to the improved sustainability of supply (Wageningen University & Research, n.d.). Despite the sustainability prospects of this technology, implementation remains slow. Some demo installations are being developed, but it will still take a long time until the technology becomes commercially available (Chang, 2021; Navigant, 2019). If we are to meet the climate goals set in the EGD and the Netherlands' missions for the top sectors to become carbon neutral by 2050 (European Commission, 2019; EZK, 2019), the implementation of this technology needs to be faster.

It is therefore, the aim of this research to understand what is hampering the implementation of these e-cracking furnaces and how these issues can be resolved. To do this, the Dutch hydrocarbon cracking industry has been analysed. As mentioned, the EZK presented five missions for these top sectors, which are in line with the national plan to become net carbon neutral by 2050. These missions are a central part of the chemistry topsector and, therefore, for the Dutch LHC industry. One part of these missions is that the top sectors need to have a carbon-neutral industrial heat system by 2050 (EZK, 2019). This makes e-cracking increasingly relevant, as this is the most prominent solution to decarbonising LHC furnaces. The Netherlands is also a particularly relevant case, due to its unique position in this industry. It is part of the Antwerp-Rotterdam-Rhine-Ruhr-Area (ARRRA) cluster. The ARRRA cluster is where 40% of the European petrochemical industry is concentrated (Port of Rotterdam, n.d.). Several hydrocarbon cracking giants, such as Shell, Dow and BASF, are active in this region. As a result, most of the pilot projects in e-cracking are also being built in and around the Netherlands, making it a key location in the implementation of e-cracking (Shell, 2022; Sabic, 2022). Furthermore, the Dutch LHC industry is part of the Dutch Chemistry topsector. This is one of the ten top sectors set up by the Dutch government. A top sector is a network in which government, industry, researchers and societal organisations collaborate to increase the competitiveness and innovativeness of the related industry (Topsectoren, n.d.). These factors makes the Netherlands one of the leading countries in e-cracker implementation and thus a relevant case study for this thesis.

Switching to electronic cracking requires not only technological change but social change as well. Innovation plays a key role in such socio-technological changes (Geels et al., 2004; Hekkert et al., 2007; Hekkert & Negro, 2009). Innovations are new combinations of knowledge which take the shape of products, services, or behaviour. These innovations do not get adopted on their own, as they face resistance and challenges from various stakeholders, might align not towards the same goal. To understand the challenges this brings, 'Innovation System (IS) perspectives' have been used in the past, such as the National Innovation System (NIS) and the Technological Innovation System (TIS) (Hekkert et al., 2007; Lundvall, 1992). However, the challenges concerning the electrification of LHC are systemic, complex and interconnected, resulting in a wicked problem (Mazzucato, 2018). Previous system perspectives have been proven to be insufficient in researching and solving these wicked problems on their own (Haddad & Bergek, 2020; Hekkert et al., 2020; Ghazinoory et al., 2020). A new framework, the Mission-specific innovation system (MIS), has emerged to further understand innovation in the context of wicked problems and missions (Hekkert et al. 2020). In such a MIS, a system surrounding a mission set to solve wicked problems and societal challenges is analysed, such as the mission to have a carbon-neutral industrial heat system by 2050 in the chemistry topsector. A MIS is defined as *"the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission."* (Hekkert et al., 2020). The performance of such a system affects how quickly solutions to the mission can be implemented. Through an analysis of such a system, barriers inhibiting the system performance can be identified. With the mission to decarbonise the industrial heat system by 2050, the MIS framework could provide valuable insights for the LHC industry. This has been done by identifying under-addressed system barriers and making (policy) recommendations to address these issues and improve system performance.

The MIS typically focuses on multiple (technological) solutions to achieve the mission. However, this research will solely focus on e-cracking since it is broadly agreed across the industry that e-cracking is the main long-term solution to decarbonise LHC in Europe. Moreover, the Netherlands is currently leading e-cracking developments with several pilot projects running at this time.

To guide this research, the following research question has been proposed:

"What systemic barriers are present in the implementation of e-crackers in the Dutch hydrocarbon sector, and how can (mission) governance be improved to overcome these barriers?"

This thesis will add to the growing body of MIS literature by applying the MIS framework in a new empirical case. As the MIS is relatively new, discoveries are still being made, and applying it to new empirical cases will increase the collective understanding of this framework (Janssen et al., 2020). A greater understanding of the MIS framework could also improve our understanding of wicked problems and help us solve more of them in the future. This research specifically contributes to the understanding of a MIS that focuses on a single technology and how a MIS functions in large, incumbent industries such as the petrochemical industry. Furthermore, this thesis will help understand how emerging, urgent transitions can be accelerated and improved to help solve societal problems. This ties in with the societal relevance of this thesis. Achieving the mission of a net-zero industrial heat system is an essential component in combating climate change. Furthermore, analysing the implementation of e-crackers could provide valuable insights that policymakers can use to encourage the electrification of other high-temperature processes as well, thus helping accelerate the broader sustainable transition across all of the Netherlands.

This thesis is structured as follows: Section two provides a background on electronic cracking in the Netherlands. Section three displays the theoretical framework used to conduct this research. Section four elaborates on which methods have been used. Section five elaborates on the results and the data analysis. The discussion section takes a moment to reflect on this research and the methods used, while also discussing avenues of future research. The final section, the conclusion and recommendations, answers the research question and discusses the recommendations made in this research.

2. The Dutch LHC industry

Before analysing the Dutch LHC industry, it is essential to understand the context in which it resides. That is why this chapter explains what the hydrocarbon cracking industry is and which developments it is experiencing. As previously mentioned in the introduction, the Hydrocarbon industry produces olefins, also known as high-value chemicals (HVCs) by using longer hydrocarbons, such as naphtha, as feedstocks (Tijani et al., 2022; ISPT, n.d.). These Olefins form the building blocks of many household products used today. It is used in plastics, medicine, perfume, food items, and more, making LHC an essential process in our current economy. The LHC industry is mainly inhabited by large, incumbent petrochemical companies and is part of the Dutch chemistry top sector. This means it adheres to the missions set in the Missions for the top sector- and innovation policy, and therefore, the mission to decarbonise their industrial heat system by 2050. The Dutch chemistry top sector is nationally represented by ChemistryNL, an agency focused on executing mission-driven policy set up by the EZK ministry (ChemistryNL, n.d.).

Currently in LHC, the feedstock used to produce HVCs is heated in a furnace using steam. This steam has a temperature of around 850 degrees Celsius, which breaks the feedstock down into HVCs. These chemicals are produced in certain ratios, which depend on the type of feedstock and the quality of the cracking process. Cracking installations are often closely connected to off-takers making changing the installation a process involving many different actors. As such, the output of cracking furnaces should preferably remain relatively constant and inflexible. There are currently 45 LHC furnaces in Europe, with a total production capacity of 25,305 kilotons of ethylene per year as of 2021. Of those 45, five are located in the Netherlands, with a total capacity of 2,736 kilotons of ethylene per year as of 2021 (Petrochemicals Europe, 2021). These five LHC furnaces belong to Shell and Dow Benelux, two of the largest petrochemical firms in the world. The furnaces in these cracking installations are usually developed by either the industry giants themselves, or a third party, such as Coolbrook or Linde. A naphtha cracking furnace is responsible for 1.8 to 2.0 tonnes of CO_2 per tonne ethylene (Ren et al., 2006). This means that the Dutch LHC industry is responsible for approximately five megatonnes of CO2 annually (Kunststof & Rubber, 2021). This process needs to be decarbonised to achieve the carbon-neutral industrial heat system planned in the Missions of for the top sectors (EZK, 2019).

Table 1.

A brief overview of the LHC capacity and emissions in Europe and the Netherlands, based on Ren et al. (2006) and Petrochemicals Europe (2021).

	Europe	The Netherlands
Amount of LHC installations	45	5
Capacity (Kt Ethylene per year)	25,305	2,736
Emissions (Kt CO_2 per year)	45,549– 50,610	4,924 – 5,472

Currently, there are three main methods of decarbonising LHC. The first method is firing the furnaces with hydrogen instead of fossil fuels. This would eliminate the carbon emissions from the heating process. The second method is using Carbon capture technology to eliminate emissions and store or utilise them elsewhere. This solution does not make the process itself emissionless, rather it (temporarily) moves the emissions to another place. This makes it more of a temporary solution. The last option is currently the most popular in Europe, namely electric cracking (e-cracking). In e-cracking, the fossil furnace gets replaced with an electric one. This solution removes all heating emissions if the electricity comes from a sustainable source. E-cracking has only recently emerged, with the first two pilot projects only starting in 2021. One project is organised by Dow and Shell (Shell, 2022), two large petrochemical firms. The other is a cooperation between Sabic, BASF and Linde (Sabic, 2022). Sabic and BASF are two other large petrochemical firms. Linde helps this cooperation by developing the technology for the cracking furnace. Conventional steam crackers currently require around 1gigajoule (GJ) of electricity per tonne of ethylene produced (Ren et al., 2006). This amount of electricity is negligible compared to the total energy demand of cracking installations, which is around 21-26 GJ per tonne of ethylene (Ren et al., 2006). Electrifying these cracking furnaces would change this, however. Industry experts estimated that an e-cracker would require between 400-600 MW of continuous electricity (Interview 7). This would increase the dependency of cracking on electricity tremendously (BASF, n.d.; Interview 5, 8). Currently, implementation rates of e-cracking are too slow to meet the goals set in the top sector missions and the EGD. Recent estimations claim that e-cracking likely needs over a decade to develop before implementation can begin (Chang, 2021; Navigant, 2019). This research aims to identify the main barriers and provide recommendations on how to accelerate this implementation so that these goals may be met.

3. Theory

This section elaborates on the theoretical framework used in this research. The underlying theory used in this research combines the Mission-specific Innovation System (MIS) and the system problem types from the Technological Innovation System (TIS) in relation to e-cracking.

3.1 Mission-specific Innovation System

Innovation systems have proven to be a valuable perspective for analysing socio-technological transitions in the past. IS literature views the development and diffusion of innovations from a systemic perspective, where multiple actors act and interact, both individually and collectively, in a so-called Innovation System. They define an IS as; "*all institutions and economic structures that affect both the rate and direction of technological change in society"*(Hekkert et al., 2007). Viewing innovation this way allows for a greater understanding of the dynamics causing systemic change or the lack thereof.

While previous IS literature remains helpful in understanding innovation, it lacks certain the ability to understand innovation dynamics regarding grand societal challenges and mission policy (Haddad & Bergek, 2020; Hekkert et al., 2020; Ghazinoory et al., 2020). Hekkert and colleagues proposed a new perspective on innovation, the Mission-specific Innovation system (MIS) (Hekkert et al. 2020; Elzinga et al., 2023). They define a MIS as '*the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission*'. This new view in IS literature builds on the technological innovation system (TIS), where the focal point of the system lies on a technology. The MIS, differs from the TIS across different analytical dimensions (Elzinga et al., 2023; Wesseling & Meijerhof, 2023). Namely the Wickedness, the Temporality and embeddedness, and the directionality (Wesseling & Meijerhof, 2023). Wickedness in the MIS comes twofold. Both a mission's problems and its solutions are contested, complex and involve uncertainty (Wanzenböck et al., 2020). This differs from the previous widely used perspective of the technological innovation system. In a TIS, the solution is already clear since it focuses on a specific technology. The temporality difference of the MIS comes from its definition. This is because missions have a time-bound goal. These missions usually have various milestones leading up to their medium- to long-term goal, around 10-30 years into the future (Mazzucato, 2018). This defined temporality makes it a unique perspective in the innovation systems literature (Frenken, 2017). The final difference, the directionality, comes from the fact that missions (should) provide clear directionality (Mazzucato, 2017). Missions give directionality to the range of solutions that can be applied to help achieve the mission. This is necessary within a system where the solution has not been determined yet. A consequence of these unique aspects is that a MIS is not immediately evident in its boundaries and in which actors are involved. This means a different methodology is necessary to analyse these systems compared to previous innovation system theories. Wesseling and Meijerhof (2023) made a start to such a methodological framework. They introduced a five-stage structural-functional approach to analyse a MIS, based on the existing structural-functional framework of the TIS (Hekkert et al., 2007; Bergek et al., 2008). These five stages have been explained below.

3.1.1 Problem solution diagnosis

The first stage of a MIS analysis is the problem solution diagnosis. In this stage, the full scope of the mission gets mapped out by analysing which societal problems are involved with the mission and which solutions are present to help solve these problems. There are two important concepts in this research stage: problem directionality and solution directionality (Wesseling & Meijerhof. 2023). Problem directionality refers to which societal problems are included and prioritised by the mission. This directionality also affects what solutions are relevant to completing the mission. Meanwhile, solution-directionality refers to the factors that influence the stakeholders in the system in how they search and invest in solutions to the problem the mission focuses on. These factors are already in place and determined by the present regulative, normative and cultural-cognitive institutions (Scott, 2013). These forms of directionality are further assessed in the system function analysis.

After assessing the relevant problems to the mission, the relevant solutions would typically be analysed. Several solutions to the mission are present in the system at one time. They can complement each other or compete. These solutions would usually be analysed in parallel to help understand the interactions between these solutions and the system as a whole (Elzinga et al., 2023; Wesseling & Meijerhof, 2023). However, due to the technological focus on e-cracking in the LHC industry, only this solution has been analysed. The result is a system with a strong technological focus aimed at achieving a mission.

3.1.2 Structural analysis

During the second stage of a MIS analysis, the structural components of the system are identified. The components of an innovation system are the actors, institutions, networks and infrastructure that play a role in the specific system (Hekkert et al., 2011). In the case of a MIS, the components play a role in developing the mission and its solutions. Wesseling and Meijerhof divide this stage of the analysis into two steps. The first step is defining the mission arena. The mission arena is "*The actors that are engaged in the highly political and often heavily contested process of mission governance (. . .) [by] providing direction to the MIS as well as mobilising and aligning existing innovation system structures into a semi-coherent ensemble that aims to pursue the mission*."(Wesseling & Meijerhof, 2023, p.3).

The actors involved in mission governance have four main tasks: Firstly, they are responsible for further *developing the mission arena*. In this task the governance structure gets formed around the completion of the mission. Secondly, they are responsible for *formulating the mission* the system focuses on. The relevant societal problems the mission arena focuses on must be included in a coherent mission, where goals and milestones are set for the other MIS actors to achieve. The third task the mission arena fulfils is *mobilising the MIS components via mission governance actions*. The mission arena actors must set up an action plan or agenda to fulfil this function. This agenda describes activities that existing innovation system components need to pursue. Furthermore, this agenda contains governance actions that can be used to enable the system components to perform these activities. The fourth task the mission arena actors perform is *continued, reflexive mission governance*. It is essential that the mission process is evaluated over time. This allows for reflection on the current mission governance so further improvements can be made. Identifying these actors provides valuable insight into which actors play the role of directing and mobilising the MIS.

Once the mission arena has been identified, defining the rest of the MIS, also known as the performance structure, becomes a pivotal task. To analyse this, the MIS framework builds on previous system frameworks. The previously mentioned structural components define a typical innovation system.

However, a common critique on previous innovation systems is that the opposing forces in the system were not taken into account (Geels, 2004; Markard et al., 2015). As such, the MIS includes both supportive and opposing forces of change. These forces influence the development and diffusion of mission solutions directly and indirectly, for various reasons and purposes, such as making progress in the mission or achieving economic gains. To include these factors, the MIS is defined as follows: a MIS is "*a temporary semi-coherent configuration of different innovation system structures that interact and affect the development and diffusion of solutions to a mission that is defined and governed by a mission arena of different stakeholders.*" (Wesseling & Meijerhof, 2023, p. 3).

3.1.3 System function analysis

Usually, this stage of the MIS is focused on assessing the system performance through the analysis of 'system functions'. System functions are defined as 'key innovation activities' that influence the innovative capabilities of an innovation system (Bergek et al., 2008; Hekkert et al., 2007; Wieczorek & Hekkert, 2012). These activities are performed by the structural components of the system. Assessing these functions gives insights into the performance and operation of the innovation system. If a function is sufficiently fulfilled, it indicates that a system has a higher innovative performance. However, if a function is not sufficiently fulfilled, it might mean that this function is forming a bottleneck for the system performance. The MIS approach would then analyse the poorly performing system functions to determine what barriers in the system are causing this and how to solve them.

This research takes a different approach. Scoring the system functions through the use of indicators before analysing problems in the system has often not provided the correct understanding of functional dynamics and causal mechanisms, and thus a more qualitative approach is preferred (Bergek, 2019). To analyse the system functions without assessing them beforehand, a deep understanding of the system barriers is required. That is why this research opts to identify the barriers in the system first and to explore their effects qualitatively, and linking them to the system functions afterwards. This method still explores the impact of the barriers on the system functions while having the barriers take a more central role. The system functions are used to formulate intervention points targeted recommendations can be focused on. This approach complements the research question's strong focus on identifying and solving barriers in the system.

TIS literature uses a set of seven system functions, which the MIS framework adapted and expanded by adding functions regarding problem directionality and solution directionality. The MIS has a greater focus on not only building up the new solutions, but also destabilising the old, unfavourable ones (Wesseling & Meijerhof, 2023). The set of seven system functions used in this research is displayed in Table 2.

Table 2.

A brief description of the MIS system functions. Based on the work of Wesseling & Meijerhof (2023), Hekkert et al. (2007), and Wieczorek and Hekkert (2012).

System function	Description
SF1: Entrepreneurial activities	Experiments undertaken by entrepreneurs to enable learning: e.g. entering markets for new solutions, innovating business models, and developing new and existing solutions
SF2: Knowledge development	Developing new knowledge through learning by searching and learning by doing. Further increasing development and understanding the societal problems and its solutions.
SF3: Knowledge diffusion	The exchange of knowledge between innovation system components through meetings, conferences, reports, etc.
SF4: Providing directionality	
4A: Problem directionality	"*The direction provided to stakeholders' societal problem conceptions and the level of priority they give it*." (Wesseling & Meijerhof, 2023, p. 9)
4B: Solution-directionality	Providing directionality to the search and development of new and existing solutions for the mission, as well as exercising coordination efforts to identify, select and exploit synergetic sets of solutions to the mission
4C: Reflexive governance	"*Reflexive deliberation, monitoring, anticipation, evaluation, and impact assessment procedures; these provide the analytical and forward-looking basis for redirecting the system's problem framing and search for solutions based on lessons learned and changing contexts. Reflexive governance can be seen as second-order directionality, can be initiated by the mission arena or by critical outsiders, and is inherently transformative.*" (Wesseling & Meijerhof, 2023, p. 9)
SF5: Market formation and destabilisation	Creation of markets for niche solutions and providing support in their development and diffusion; destabilising markets for harmful practices and technologies present in the system
SF6: Resource (re)allocation	The mobilisation of resources (human, material, and financial) to support the other system function activities
SF7: Creation and withdrawal of legitimacy	"*Creating legitimacy for prioritising (a) the problem and (b) the development and diffusion of the solutions, at the cost of harmful practices and technologies*" (Wesseling & Meijerhof, 2021, p.13). Through support from stakeholder groups, the public, and other actors.

3.1.4 System barrier analysis

The fourth stage of a MIS analysis consists of identifying and analysing system barriers. Through the system barrier analysis, it becomes clear what problems are hampering the performance of system functions. This starts with identifying the system barriers (also known as systemic problems). System barriers are often components, such as actors, networks, institutions or materialities, that are not sufficiently present to enable system functions (Wieczorek & Hekkert, 2012). They can cause system functions to underperform, thus inhibiting the mission progress. If multiple interrelated systemic barriers persist, they could cause systemic lock-in. This makes transitioning to a new system increasingly more difficult as the system gets more locked in (Wesseling & Meijerhof, 2023).

3.1.5 Recommendations and conclusions

In the fifth and final stage, solutions to improve system performance are proposed. Through the analysis, it becomes clear what is inhibiting the system from performing better and what the system is missing to solve the barriers. Solutions, also called systemic instruments, can be (innovation) policy or other governance actions the mission arena actors can undertake. Governance actions can be undertaken ex-ante ex-post or during the existence of the MIS. These instruments should not be utilised to treat the symptoms of the systemic barriers, but they should target the root causes (Wesseling & Van der Vooren, 2017). This results in formative recommendations on how to adequately adjust mission governance to address the remaining problems, thus increasing system performance.

3.1.6 The e-cracking MIS

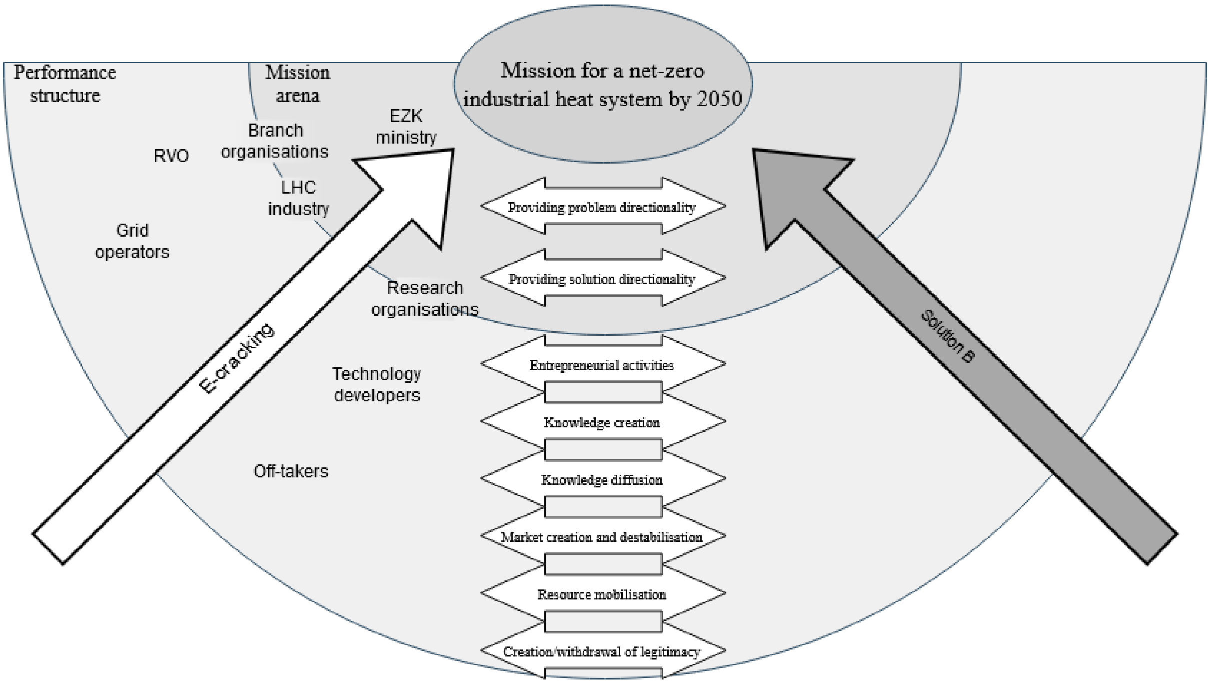

Figure 1. E-cracking focused MIS framework, adapted from Elzinga et al., 2023 and Wesseling & Meijerhof (2023).

Elzinga and colleagues (2023) proposed a framework to summarise and analyse a MIS. When using this framework on the MIS of this research, it shows some key differences compared to the adapted MIS as described above and in Figure 1. Generally, the first stage of a MIS, is dedicated to mapping out different solutions to the missions (Wesseling & Meijerhof, 2023). However, as mentioned, the solution in the LHC sector is already clear. E-cracking is the de facto solution chosen within the EU. This leads to a specific technological focus in this research. Because of this technological focus, the system surrounding the one solution shows similarities to a TIS within the context of a larger MIS. The resulting MIS is shown in Figure 1.

3.2 Systemic problem types

Due to the technological focus of this MIS, the TIS literature has some valuable insights for analysing the barriers in the system. TIS literature differentiates between four types of systemic problems (Wieczorek & Hekkert, 2012). The first kind are Actors' problems, which can be presence or capacity-related. Presence-related actor problems concern the lack of potentially essential actors in the system. In this case, certain activities required for the system to perform remain incomplete and negatively impact or prevent system performance. An example of this could be a lack of construction companies to build projects other actors have planned. Capacity-related actor problems are more concerned with the capabilities of the actors present. They may lack certain competencies that are required for a smooth innovation process.

Secondly, there are institutional problems. Institution problems concern hard (rules and regulations) and soft (culture and relations) institutions. Institutional problems can also be presence or capacity-related. Presence-related problems mean that specific institutions might be absent, meaning that certain problems remain (under)-addressed, causing further problems in the system. Capacity-related institution problems concern the quality of present institutions. Too strict regulation might hinder innovations while supporting a lock-in, and weak institutions might not give enough support for innovations to flourish.

The third kind of problem are interaction problems. These problems are related to the interactions between different actors in the innovation system. Interaction problems can be presence or quality related. Presence-related interaction problems mean that interactions between actors are missing. This can be caused by a number of reasons, such as a lack of trust, differing or conflicting objectives, capacities, or unawareness. Quality-related interaction problems mean the quality or intensity of interactions between actors is problematic. Too strong ties between actors can work as a reinforcement of system lock-in, while weak ties can be a hindrance to development and collaboration.

Finally, there are infrastructural problems. Infrastructural problems refer to problems not only with physical infrastructure but also with financial and knowledge infrastructure. Infrastructural problems can be presence and quality-related, with presence-related problems concerning missing infrastructure, while quality-related problems concern inadequately performing or malfunctioning infrastructure.

Understanding what kind of problems are present in the system is particularly relevant for this thesis, as it helps understand where the barriers come from and what their broader effects are on the interconnected, complex system of the Dutch LHC industry. Sometimes, one of these problems can affect multiple system functions in several different but connected ways. Understanding the broad, interconnected nature of these problems can help develop targeted solutions for them in the final phase of this research.

4. Methods

4.1 Research design

The system surrounding the mission to achieve a sustainable industrial heat system in the chemistry sector by 2050 has been analysed by using case study with a qualitative research approach (Bryman, 2012). This research follows a modified version of the MIS approach described in the theory, where a strong focus lies on the barrier analysis instead of assessing the overall system performance. This section provides an overview of the methodological steps behind this research.

4.2 Data collection methods

The first data collection method was **desk research**. This desk research used industry press, company reports, and government articles to gather data on the Dutch LHC industry and its actors. Building this background of information was necessary to interview actors based on their relative experience. It was essential to understand both the technology and the context in which it resides. This meant respondents in the interview stage would not have to spend the limited time explaining those subjects.

The second data collection method used in this research was **expert interviews**. These were conducted in cooperation with the Royal Association of the Dutch Chemical Industry (VNCI). Through this collaboration, I was able to join interviews with expert respondents from the industry. We conducted the interviews together, where I was able to ask questions about barriers inhibiting e-cracker implementation and their effects. In return, I assisted in writing the thought-leadership paper the VNCI is working on. Interview respondents were chosen using purposive sampling. This is a non-probability form of sampling where respondents are selected deliberately based on their expected relevance to the research (Bryman, 2012). This ensured that respondents were relevant to this research. Where possible, respondents were chosen from different levels of the Innovation system to gain a broad perspective. The final list of respondents can be found in Table 3. The industry experts are all actors in the LHC industry within the ARRRA cluster, the industrial chemistry region the Netherlands is a part of. They have been anonymised as per their request, and are referred to as Industry actor 1 through 4. Actors focused on technology development, such as Linde or Coolbrook, were not available for this research. However, some of the interviewed industry actors are involved in technology development as well, meaning they also have an awareness of prevalent barriers in this part of the system. As e-cracking mostly faces systemic issues surrounding implementation, rather than with the technology itself, the exclusion these actors should not have a critical impact on this research.

Table 3.
List of interview participants.

Interview	Organisation	System-level
Interview 1	VNCI	Intermediary
Interview 2	TNO	Research Organization
Interview 3	EZK	Governmental
Interview 4	EZK	Governmental
Interview 5	TenneT	Infrastructure
Interview 6	Industry actor 1	Industry
Interview 7	Industry actor 2	Industry
Interview 8	Industry actor 3	Industry
Interview 9	Industry actor 4	Industry

The interviews were focused on identifying the system barriers and their effects. To assist in this, the interviews were conducted in a semi-structured format. After the VNCI asked their questions, I was able to ask additional questions. These questions were focused on identifying system barriers and their causes and effects instead of scoring the system functions. The semi-structured interview format left room for follow-up questions, should relevant questions emerge during the interviews. The interview guide can be found in Appendix I. Using the interview guide ensured data collection happened consistently and reliably. This ensured the data collection was as complete as possible. The resulting data allows the most impactful and relevant barriers to be identified. As transcripts and recordings were not possible, meeting notes were made during the interviews to ensure relevant data could be recorded for this research. These notes summarise data relevant to finding the barriers and relevant details of the innovation system. This allowed valuable insights from these interviews to be used in the data analysis.

4.3 Data analysis

This research used a modified, barrier focused MIS approach. In this modified approach, the usual problem and solution diagnosis of the MIS framework has been replaced by a short problem diagnosis, as the solution is already predetermined. The functional analysis has been changed to primarily focus how the system functions relate to the identified system barriers, rather than scoring system functions. This way the system functions have been used as key points to set up recommendations. The steps of this analysis are elaborated on below.

4.3.1 Problem diagnosis

The first step in analysing the innovation system consisted of mapping out the scope of the mission central to the system. This has been done through desk research using policy documents. Specifically the document containing the focal mission of this research; reaching a net-zero industrial-heat system by 2050 (EZK, 2019). As mentioned, this step of MIS analysis usually also focuses on identifying the available solutions to the mission. However, due to the strong focus on e-cracking in the Dutch LHC industry, this step has been excluded from this research.

4.3.2 Structural analysis

The second step of the System analysis was examining the innovation system structure. To identify the components of the mission arena, policy documents have been reviewed, with further complements from the interview data. To assess the components comprising the rest of the innovation system, industry press, company reports, and internet sources were used in the desk research to understand the system surrounding the Dutch LHC industry. The data gathered from this desk research consists of data regarding important actors in the system, the present infrastructure, the networks actors are a part of, and which main developments are taking place in the system. Analysing the structure of the innovation system was essential to understand the system, and how barriers could potentially affect the system's performance. With this in mind, the research moved on to the System Barrier analysis.

4.3.3 Problem identification

As elaborated in the theory, this research opts for a method where the system barriers are qualitatively analysed, before using the system functions to gain a deeper understanding of their impact on the system. The interview data has been used to identify the barriers in the system. Every barrier mentioned in the interviews was recorded in the interview notes, together with their causes. These identified barriers were then mapped out in a ‘Systemic barrier map’ (Figure 3) which displays every barrier in the system. Using the data, connections between barriers were also found. These were also displayed in the barrier map. With this, the map shows the causes and the interconnectedness of different barriers, helping to further understand them.

4.3.3 System problem type analysis

After identifying the existing system barriers, they have been analysed using the theory to gain a deeper understanding of them. This has been done by matching each cause of the central barriers with the corresponding systemic problem types from Hekkert and Wieczorek (2012). The causes have been targeted, as solving the root causes is central to solving systemic problems (Wesseling & Van der Vooren, 2017). This provided valuable insights into what proposed solutions must bring to the system.

4.3.4 Functional connection of the barriers

Now that the barriers have been understood, the system functions have been used to determine intervention points targeted recommendations can focus on. This has been done by labelling each of the underlying causes of the central barriers with the MIS functions. This shows how the barriers relate to each system function and what impact they have on the overall MIS performance. This information can be used to keep relevant system functions in mind when proposing solutions to the system barriers. Next, the findings from the system barrier analysis have been used to connect the found problem types with the system functions. This shows what specific problem types affect system performance and in what way. This helps understand what kind of solutions need to be brought to the system, and how those solutions will affect system performance.

4.4 Recommendation phase

After the barriers and their causes have been identified and understood, systemic instruments have been proposed to solve the barriers. The proposed instruments have not only been chosen to address the barriers, but also aim to solve the root cause of the underlying problems. In time, this should eliminate the barriers and their effects, thus improving system performance and mission progress.

5. Results

This chapter discusses the results of the innovation system analysis. First, the results of the problem diagnosis are presented, followed by the structural analysis results. Then, the problem identification and system problem type analysis are discussed. The final chapter presents the impact of the identified barriers on the system functions.

5.1 Problem diagnosis

The mission at the centre of this MIS is to achieve a net-zero industrial heat system by 2050 (EZK, 2019). It is one of three sub-missions to achieve the main mission climate-neutral resource, product and process system in the industry by 2050, which is one of five main missions set in the 'Missions for the top sectors- and innovation policy'. These five missions aim to help solve the societal challenges of climate change and to the waste and increased scarcity of valuable resources. This main mission has a list of intermediate goals to be achieved by 2030 as well. In 2030, the industry must use 50% fewer primary resources. Additionally, the greenhouse gas emissions of production processes and the waste sector must be reduced to 36 Mton CO_2. Finally, the industrial heat system up to 300 degrees Celsius must be decarbonised by 2030. With the scope of the mission in mind

5.1 Structural analysis

The MIS consists of two main components: the mission arena and the broader innovation system. Usually, the broader innovation system involves several different MIS solutions. In this case, the Dutch LHC industry has a strong technological focus on e-cracking, which made it the de facto solution in the EU. The actors involved in the mission arena shape the innovation system around the mission and mobilise the various system components to achieve mission success. In this case, the mission arena has one main actor leading it, the EZK ministry. The ministry of EZK fulfils all four roles of a mission governance actor in the Mission Arena: further developing the mission arena, formulating the mission, mobilising MIS components, and reflexive governance.

They are the leading actor that formulated the sustainability goals the industry has to adhere to. They created the missions for the top sector policy, which the mission to achieve a carbon-neutral industrial heat system by 2050 is a part of (EZK, 2019). In formulating the mission, they worked with another key stakeholder of the chemistry industry, ChemistryNL, the top sector agency for the Dutch chemistry industry (RVO, 2022). The ministry of EZK is also involved in expanding the mission arena. They are actively trying to involve more parties in policymaking by collaborating with key system components, like ChemistryNL, to reflect and formulate previous and future policies (ChemistryNL, n.d.). Other key actors involved in these processes are branch organisations representing the broader industry, such as the VNCI, alongside research organisations, such as TNO, and large industry actors, such as Shell and Sabic. These actors write advisory documents to the government so their interests are represented when reflecting on existing policy and when future policy is being made (Shell, 2023; VNCI, 2021). The branch organisations are also strongly involved in mobilising system components to achieve their mission, as they can communicate with their members to motivate and support them in their endeavours. They often do this through their trade magazines and newsletters. An example of this is the VNCI posting news messages on how electrification is the best way to decarbonise the energy and heat demand of the industry (Broekhof, 2023)

Through their actions, the mission arena actors shape the context in which the e-cracking innovation system resides. This system consists of several structural components, some overlapping with the mission arena. The system is structured similarly to a TIS, where networks of actors act and interact under specific rules and infrastructures (Hekkert et al., 2007). The main components of this IS are the government, firms involved in the LHC industry, technology developers, research organisations, off-takers, and actors related to the infrastructure. The government is particularly involved in defining the rules and missions that the industry adheres to. They are the main regulatory body, and the most influential component of the government in this industry is the aforementioned ministry of EZK. Another important government actor is the Netherlands Enterprise Agency (RVO). The RVO is responsible for distributing subsidies. Among these subsidies are subsidies for green chemistry as well (RVO, 2023). The LHC industry consists of large industry incumbents, such as Shell and Dow, that want to implement e-cracking to decarbonise their industrial heat systems. They produce high-value chemicals (HVCs) that are used to produce various other chemicals, compounds and products. These companies primarily work on their own, and are very reluctant to work together. Partnerships do happen between industry actors, but ideally, they want their partners to learn as little as possible from the partnership (Interview 2; Steenbakkers, 1997). Some partnerships have started for e-cracking pilot projects, providing essential research for this technology. Further research and development for this is provided by research actors, such as TNO, and technology developers. The technology developers supply the LHC industry with the technology for cracking and, therefore, play a key role in developing e-cracking furnaces. One example of these technology developers is Coolbrook, who recently developed a new technology that can heat furnaces to up to 1700 degrees Celsius (Coolbrook, n.d.). The LHC industry often contracts these technology developers to design or collaborate with them on their cracking furnaces. Some technology developers are also directly involved in the aforementioned ongoing e-cracking pilot projects in the LHC industry (Shell, 2022; Sabic, 2022). The demand side in this system consists of off-takers. Off-takers buy HVCs and produce other goods, such as plastics and medicine. The leading relevant infrastructure organisations in this system are grid operators, such as TenneT. They operate and maintain high-voltage electricity grids, that new e-crackers depend on (TenneT, n.d.). Through these components' actions and interactions, the e-cracking innovation system operates within the boundaries set by the mission arena. A brief overview of the innovation system is displayed in Figure 2.

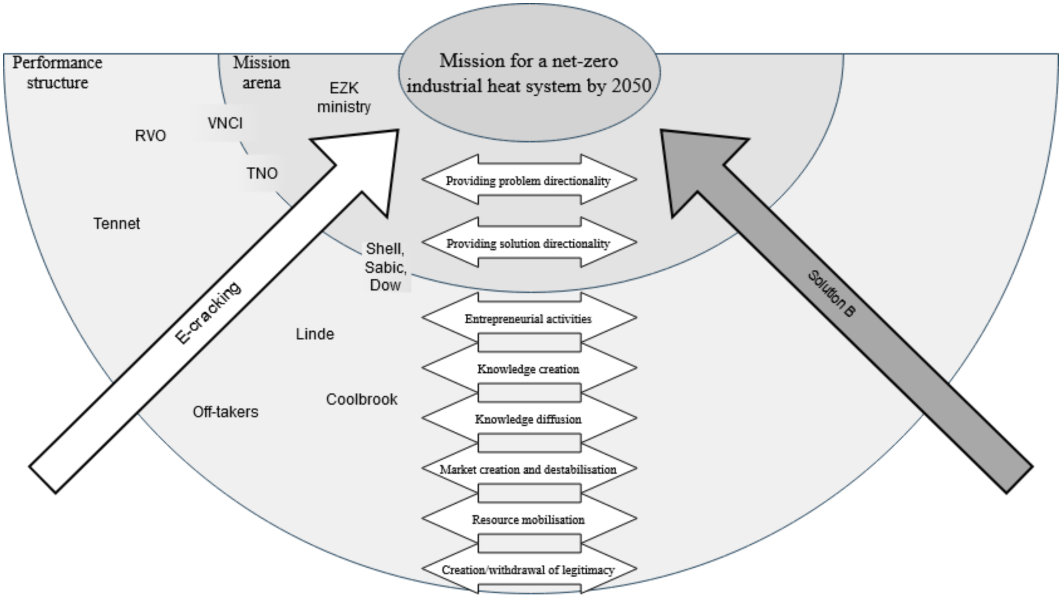

Figure 2: Overview of the analysed e-cracking MIS. Adapted from Elzinga et al. (2023) and Wesseling and Meijerhof (2023).

Now that the structure of the system has been analysed, its components can be understood in relation to the system functions they fulfil. The LHC industry has primarily been concerned creating entrepreneurial activities alongside the creation and diffusion of knowledge. They also mobilise resources in the system to facilitate these activities. The intermediary organisations, such as branch organisations, are primarily tasked with facilitating knowledge diffusion and the creation of legitimacy, as they try to reach and inform their members of new developments in the system. Off-takers are one of the key components in market formation, as they are the main buyers of the goods produced in this industry. Technology developers help fulfil the knowledge creation and diffusion function through research and development used by the industry. This technology and research is spread throughout the system via contracts and purchases. They also participate in industry partnerships to exchange knowledge and collaborate on further technology development. Research organisations further help with knowledge creation and diffusion. They conduct studies on new to further fill in knowledge gaps, and distribute this knowledge in reports and articles. Research organisations are also known to lend their capabilities in pilot projects. A recent example of this is TNO helping in the pilot project of Dow and Shell (Shell, 2022). Grid operator primarily allocates resources to build and maintain the infrastructure the system relies on. Finally, there’s the government. The ministry of EZK primarily provides problem and solution directionality and reflexive governance through the mission policy that they write. They also draw up subsidy regulations, which are then executed by the RVO to help mobilise resources. The ministry of EZK is also strongly involved in market formation and destabilisation through its policy, playing a vital role in fulfilling the system functions.

The system surrounding cracking has been very efficient in the past. The LHC industry has had decades to perfect it, forming efficient infrastructure and a solid knowledge base. Now, fossil fuels are being phased out, and their current ways of heating cracking furnaces must change to a novel technology, namely e-cracking. The system is preparing for change, as pilot projects are finally proving the potential of e-cracking (Shell, 2022; Sabic, 2022). Despite these efforts, the system remains rigid and difficult to change, with some parts proving insufficient, like the infrastructure (Interview 2, 3, 5, 6, 8). As a result, some functions are not optimally fulfilled, and the implementation rate of e-cracking is slowing. Current development is going too slow, likely meaning it will be another decade before e-cracking becomes commercially viable (Chang, 2021; Navigant, 2019). The next part of this research aims to understand what barriers are currently inhibiting the system from fulfilling its functions and shifting to e-cracking at a faster rate, so that the system may achieve the mission of having a net-zero industrial heat system by 2050.

5.2 Problem identification

During the interviews, several system-inhibiting barriers were found. Seven of these barriers took a central role in the system. They were consistently mentioned during the interviews. The identified barriers are displayed in Figure 3. The arrows show each of the barriers are related to each other and to contextual factors in the system. The most critical problems are displayed in dark red, with underlying causes indicated in light red, and contextual factors in green. Contextual factors, such as the commodity good nature of LHC products, are decided outside of the scope of this system and cannot be changed by policy recommendations. These factors are still connected to some of the system barriers, and are therefore displayed separately in the green. The barriers and their relations to each other have been further described below.

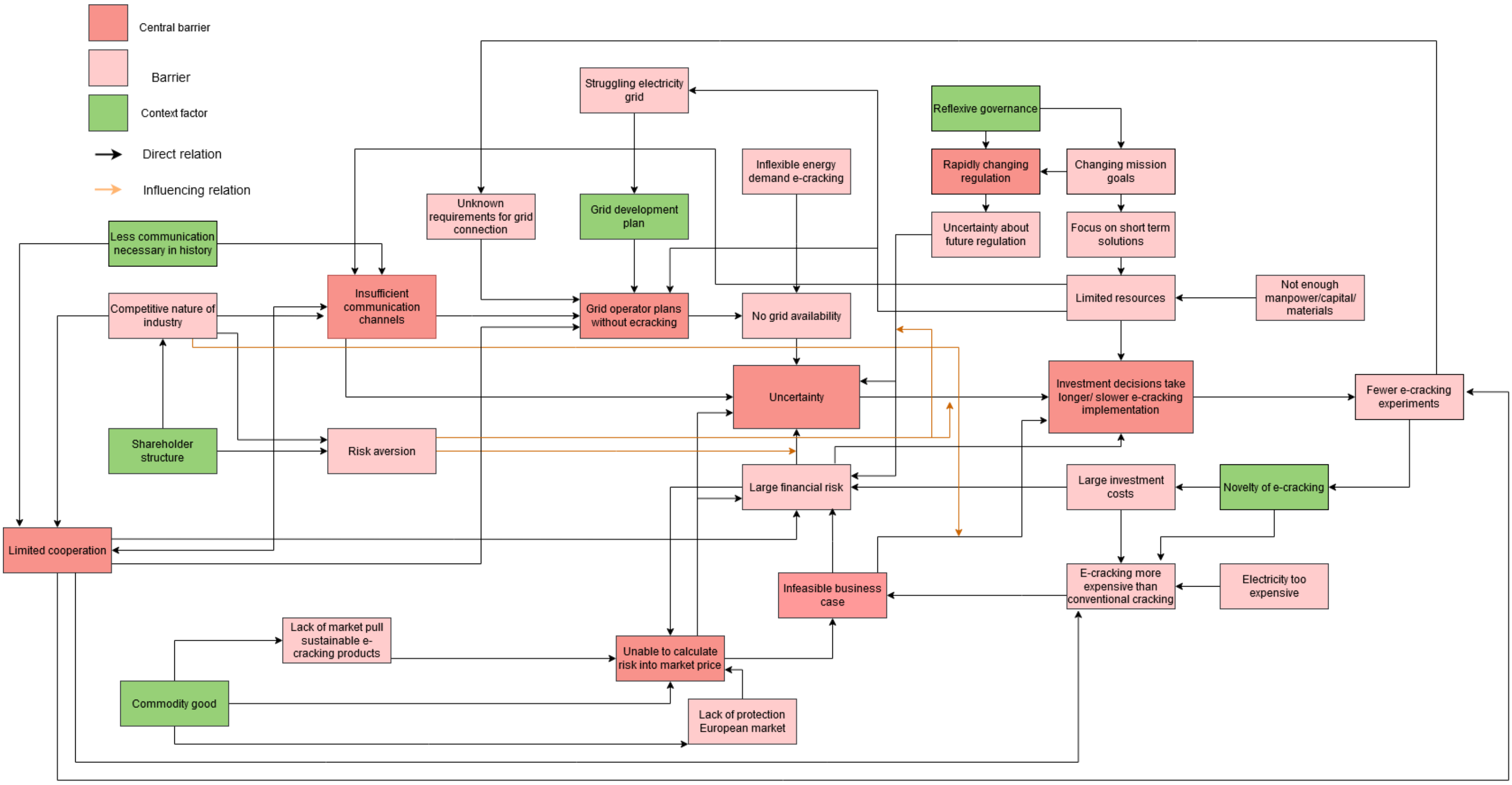

Figure 3: A map of the barriers and their causes. Based on interview data and desk research.

The first central system barrier is business case for e-cracking. This is currently infeasible due to several problems. First of all, fossil fuel-powered heating is presently cheaper than electric heating (Interview 2, 6, 8, 9). A significant reason why e-cracking is more expensive is the novelty of the technology (Tijani et al., 2022). E-cracking was long thought to be an infeasible technology, and has only recently emerged as a serious contender to decarbonise the LHC process (Interview 1, 6). If more projects undertaken, the technology would have been more developed and e-cracking would have been more affordable than it currently is (Kagan, 2023). As e-cracking is an emerging decarbonising solution, there is still a lot of learning and optimising to be done, in contrast to fossil-powered cracking that has had decennia to improve. Furthermore, the operational costs of an e-cracking installation are largely dependent on the electricity price (Navigant, 2019; Interview 6). Electricity is currently too expensive to compete with fossil fuels (Interview 2, 6, 8, 9). As a result, running a fossil powered LHC plant is currently cheaper than an e-cracking plant (Tijani et al., 2022). This is further reinforced by the fact that implementing e-cracking is incredibly capital intensive to begin with. An e-cracker costs multiple billions (Navigant, 2019; Interview 8) and to transition from fossil fuel tailored infrastructure to new cracking technology exacerbates this (Interview 2, 6). Combined with the previously mentioned lack of profitability compared to a conventional cracking furnace, these barriers pose a significant financial risk that companies will be unlikely to take (Interview 6, 8). It is more beneficial for them to keep their current crackers for as long as possible (Interview 2). As a result, there are fewer e-cracking projects in this industry, meaning there are fewer opportunities to research and develop e-cracking to bridge the gap it has with conventional cracking.

The second central barrier reinforces this problem. In many cases, increased risks and costs could be reflected in the market price. However, for LHC products this is not the case. They are commodity goods (Interview 8) where the quality of products does not differ meaningfully, regardless of the production process (Fernando, 2024). They are interchangeable with goods from other producers without issues. These goods also compete in the global market, meaning if Dutch LHC companies changed to e-cracking, their products would become more expensive without an increase in quality. This combined with limited client willingness to pay more for sustainable goods (VNCI, 2021), likely means that a price increase drives clients away to cheaper sellers (Interview 6, 8). There is currently no system in place to protect sustainable cracking in the European market. This makes it challenging to sell sustainable products at a higher price in this market (Interview 2, 6, 8, 9). This lack of a protected, lucrative market makes the industry less inclined to engage in new e-cracking projects.

The third central system barrier is that e-cracking implementation is currently not factored into electricity grid development plans (Interview 2, 5). The electricity grid in the Netherlands is currently struggling (Voorhoeve, 2022). It is overloaded and insufficient to facilitate the transition to e-cracking. Current grid congestion maps show that large parts of the country have limited to no extra room for new projects (Netbeheer Nederland (n.d.). The main grid operator, TenneT, wants to improve the grid, but they lack the financial, human, and material resources to do so (Interview 5, 7). They have bought out cable manufacturers' inventories for the next few years, which is only enough to facilitate their currently planned grid improvements (Interview 5), not potential e-cracker implementation. Personnel shortages are also causing delays in grid expansion projects, thus compounding the barrier against e-cracker inclusion in grid expansion plans (Mastenbroek, 2022). The energy demand of the LHC industry also makes it difficult to include in grid expansion plans. The intermittent nature of renewable energy means the grid will be under more stress during some moments than others. As a result, the grid would benefit most from a flexible energy demand (Netbeheer Nederland, 2024; Interview 5). Unfortunately, the energy demand of the LHC industry does not fit this pattern. The demand is large and inflexible (Chang, 2022; Interview 7). Current estimations project that a state-of-the-art e-cracker would require 400-600 MW in continuous electricity demand (BASF, n.d.; Interview 7). The inflexibility of this demand makes it more challenging to include e-cracking in the electricity grid expansions.

Additional troubles in including e-cracking into grid expansion plans arise from a lack of communication. For the industry to implement e-cracking right now, the plans should have been discussed with the grid operator much earlier, but this has not transpired. Grid operator TenneT plans ten years ahead, allocating their resources to where they think they are most necessary (Interview 5). Due to this lack of communication, these resources have already been allocated without e-cracking originally in mind, resulting in uncertainty within both TenneT and the industry. TenneT wants to know the grid requirements before planning anything, while the industry wants to make plans detailing such requirements after receiving confirmation of what the grid will look like. This has led to a stalemate between both parties (Interview 5, 6, 7, 8).

In the past, cracking only used a fraction of the electricity that e-cracking demands (BASF, n.d.; Interview 5, 8, 9). This means there was little communication required between the grid operator and the industry. In the case of e-cracking, a grid operator would not have an indication of how much energy the LHC industry would require to electrify, due to this historic lack of communication (Interview 5). The industry is unfamiliar with how TenneT communicates, causing a gap in vital information and their subsequent inability to facilitate the required grid updates (Interview 5).

This lack of communication channels extends beyond the relationship between the industry and the grid operator (Interview 2). The industry is rather opposed to sharing information outside of limited partnerships. There is often not a lot of knowledge management going on between industry actors (Ahmad & Dafous, 2010; van Erp, 2017) as the LHC industry is very competitive in nature (Interview 1, 2). Sharing information could be detrimental to the competitive advantage firms may have over one another, resulting in a lack of proper infrastructure for sharing knowledge within this industry. This lack of communication channels is the fourth central system barrier to e-cracker implementation. The interviews further confirm this. One of the respondents mentioned that even if the actors were willing to share information, they often do not have the time or resources to do so (Interview 7). This means potentially vital and beneficial knowledge cannot be diffused, and potential knowledge asymmetry may occur, where one side of the system has more knowledge of ongoing developments than the other (Interview 2, 8). For example, the policymakers could be missing crucial information that the industry possesses to make effective policy.

The fifth central barrier also arises from the competitive nature of the LHC industry, namely the uncooperative mindset in the LHC industry. As previously mentioned, there are only two active cooperative e-cracking pilot projects (Shell 2022; Sabic, 2022). Outside of these projects, the industry is rather opposed to collaborating, as it would be detrimental for their competitive advantage (Interview 2, 8). These large industry incumbents must report to shareholders, who want to see a return on their investments. This means that they are more inclined to put profit and beating the competition before working together to achieve a societal mission (Interview 8). Industry incumbents do not perceive the mission as urgent enough to prioritise over their own current goals. As a result, the industry stays competitive, meaning they will not focus on cooperating (Interview 9).

The history of the industry further reinforces this. In the past, there were no societal missions that the industry had to unite for. Mission-based policy only recently emerged in response to the increasing prominence of societal challenges (Janssen et al., 2020; Kattel & Mazzucato, 2018). These are unprecedented times for the industry. Partnerships only occurred for the betterment of oneself, and ideally, companies would have their partners learn as little as possible (Steenbakkers, 1997). This steadfast mindset causes limited cooperation, with large amounts of research and investments being conducted independently, and possibly redundantly (Interview 2). Vast sums of valuable knowledge are currently being kept instead of shared, making potentially essential breakthroughs exclusive their innovators. This diminishes the economic feasibility of e-cracking, as (financial) risks are not shared, with every firm having to bear the burden of developing e-cracking projects on their own (Interview 2). As a result, fewer projects are being conducted in this field. The two active pilot projects are a step in the right direction for this barrier, but more and broader cooperation would be beneficial in accelerating the implementation of e-cracking.

Alongside the industry another transition is ongoing, namely a regulatory transition. Current regulations require considerable adjustment due to the quickly changing industry, with new information being learnt every day (Interview 3). Regulators adjust policy using this information to best guide the transition to a sustainable economy. These rapidly changing regulations, result in uncertainty in the industry as to how they will have to conform to new regulations and what impact these will have on their future (Interviews 2, 7, 8). These rapidly changing regulations form the seventh central barrier the industry. They raise concerns for companies over the longevity and profitability of their planned investments, resulting more deliberation and delay in investment decisions (Engau & Hoffman, 2009; Teisberg, 1993). Critical policy for the profitability of e-crackers is currently still in development or non-existent (Interview 6, 7, 8). Since LHC products are globally traded commodity goods, more certainty is required about how the European market will be protected against global competition. and how punitive policy for fossil fuel-fired cracking will make the business case for e-cracking more appealing (Interview 6, 7, 8). Further uncertainty surrounding regulations comes from the rapidly changing mission goals set by the government, who have repeatedly tried to set earlier short-term goals. This puts the industry under intense pressure to do anything in its power to meet these goals (Interview 2, 4). Whilst this sounds beneficial, it forces the industry to look for different solutions to meet the short-term goals, even if these are less desirable in the long term (Interview 2, 8, 9). This leads to already scarce resources being invested in a temporary solution instead a final long-term solution. The inconsistency of government mission goals forces the industry to split its focus between short and long term solutions, wasting precious time and resources that could otherwise be dedicated to the implementation of e-cracking.

Nearly all of the central barriers tie in under the theme of uncertainty. The industry is risk-averse. It is reluctant to engage in investments that are uncertain to yield results (Interview 2, 6, 8). The risk averseness of the industry is understandable, since companies must make profits to ensure their future. Unfortunately, this aversion only makes the mission of decarbonising the industrial heat system of the LHC industry by 2050 more challenging. The uncertainty regarding the business case, the electricity grid, and future regulations creates a larger general uncertainty and risk that the industry is unwilling to accept. This uncertainty is one of the most significant reasons that e-cracking investments take longer than desired. Large transitions come with uncertainty, but reducing these uncertainties where possible is critical to speeding up this transition.

5.3 System problem type analysis

To understand the nature of the system barriers, they have been analysed in further detail. Additionally, the system barriers have been connected to the systemic problem types from Wieczorek and Hekkert (2012) (3.2 Systemic problem types), to further understand what is missing in the system. These problem types are actor, institution, interaction, and infrastructure problems. The insights from this analysis help understand what solutions must bring to the system. The results of this are displayed in table 4, and have been discussed further below.

The incalculability of risk to be included in the market price of LHC products is related to institutional problems in the MIS. There are several presence and capacity-related problems for hard institutions. There is currently a lack of policy protecting the market competitiveness of sustainable cracking products, while punitive policy discouraging fossil cracking is too weak. This is reinforced by a capacity-related soft institution problem. This problem shows in the culture of the off-takers, who are unwilling to pay more for sustainable goods. *The infeasibility of the e-cracking business case* is caused by institutional problems, interaction problems, and actor problems. The institutional problems are rooted in the same causes as the incalculability of the risk into the market price, namely the lack of protective and punitive policy in the system. The actor problems are capacity-related and are attributable to industry actors' lack of knowledge on optimising e-cracking. This is closely related to the interaction problems, which are both presence and capacity-related. The presence and capacity of (cooperative) e-cracking projects remains insufficient. More cooperation would also lead to shared, and therefore reduced risks, making the e-cracking business case more attractive. The third central problem, *The absence of e-cracking in the grid expansion plans,* is caused by both actor, interaction and infrastructure problems. The actor problem is capacity-related and stems from a lack of knowledge. The interaction problems are both quality and presence of interaction related, as the industry and grid operators do not interact enough to sort out the uncertainty regarding the grid requirements. Finally, there is a presence-related infrastructure problem with the previously mentioned insufficient knowledge infrastructure.

For the fourth central problem, *lacking communication channels*, the problems relate to actors, institutions, and interactions. The institutional problems are related to the capacity of soft institutions in the system, as the current industry culture does not prioritise the Netherlands' mission over competition. Finally, the interaction problems are presence related. The aforementioned limited historic communication in the LHC industry means there were not enough interactions to fully develop communication channels and a cooperative mindset. The final problem is a capacity-related actor problem. Actors have shown that they do not always have the resources and human capital to transfer knowledge to other relevant actors. *Limited cooperation* shares the institution and interaction-related problems with the lack of communication channels, but does not share the capacity related actor problem. For the sixth central barrier, the *rapidly changing regulations,* the causes are institution and interaction problems. The institutional problems are capacity-related. The regulation needs to change so often because current regulations are not sufficient to facilitate the transition to e-cracking. This is further reinforced by the interaction problem. The policymakers could make better policies if they had more information about developments in the system, but there are not enough interactions to facilitate that, resulting in a presence-related interaction problem. The final barrier, the general *uncertainty*, emerges from actor, interaction, infrastructure, and institution problems. Presence and capacity related institution problems come in the shape of the missing and insufficient regulations, while weak presence of interactions originates from the lack of risk sharing in the industry. The grid uncertainty emerges from a capacity related infrastructure problem, and a presence related interaction problem. Finally, regulatory uncertainty emerges from a combination of the weak presence and capacity of institutions, and a presence related interaction problems.

This analysis has shown what the system is missing to solve the central barriers. It has also shown that institution and interaction-related problems are the most common barriers in the system. When proposing solutions to the barriers, these problem types should be considered.

5.3 Functional connection of the barriers

Now that the system barriers have been understood in greater detail, they have been connected to the seven system functions from Wesseling and Meijerhof (2023), to further understand the effects of the barriers on the system performance. These system functions show intervention points in the system, forming the basis for the recommendations. The results of this are displayed in Table 4 and are discussed in greater detail below.

Table 4.

Overview of problem type analysis and the functional connections of the barriers.

Central problems	Underlying cause	Problem type	System function
Incalculability of financial risk into the market price	lack of regulation protecting the sustainable e-cracking market from global competition	Presence-related (hard) institutional problem	SF5: Market formation and destabilisation
	Policy destabilising fossil-fired cracking is not strong enough	Capacity-related (hard) institutional problem	SF5: Market formation and destabilisation
	Lack of willingness in the market to pay more for sustainable products	Capacity-related (soft) institutional problem	SF5: Market formation and destabilisation

Infeasible business case for e-cracking	Lack of e-cracking projects to develop the technology	Presence-related interaction problem	SF1: Entrepreneurial activities
	Lack of knowledge to optimise e-cracking	Capacity-related actor problem	SF2: Knowledge creation
	Limited cooperation	Presence and capacity-related interaction problem Presence and capacity-related institution problem	SF2: Knowledge creation SF3: Knowledge diffusion SF6: Resource allocation
	Incalculability of financial risk into the market price	Presence and capacity-related institution problems	SF5: Market formation and destabilisation
	Large investment costs to implement e-cracking	Capacity related-actor problem Presence and capacity-related interaction problem	SF6: Resource allocation
Lack of e-cracking grid expansions	Unknown grid requirements	Presence and capacity-related interaction problem Presence-related infrastructure problem	SF2: Knowledge creation SF3: Knowledge diffusion
	Insufficient communication channels	Presence-related infrastructure problem	SF3: Knowledge diffusion
	Insufficient resources for additional grid expansion	Capacity-related actor problem	SF6: Resource allocation
Insufficient communication channels	History of limited communication in the LHC industry	Presence-related institution problem	SF3: Knowledge diffusion
	Mission is perceived as less urgent than conducting business as usual	Capacity-related (soft) institution problem	SF7: Creation and withdrawal of legitimacy
	Not enough resources and manpower to effectively communicate	Capacity-related actor problem	SF6: Resource allocation
Limited cooperation	History of limited communication in the LHC industry	Presence-related institution problem	SF3: Knowledge diffusion
	Mission is perceived as less urgent than conducting business as usual	Capacity-related (soft) institution problem	SF7: Creation and withdrawal of legitimacy
Rapidly changing regulation	Limited knowledge sharing in the system	Presence and capacity-related interaction problem	SF3: Knowledge diffusion
	Frequent adjustment of regulations through reflexive governance	Capacity and presence-related (hard) institution problem	SF4: Providing directionality
Uncertainty	Financial risk	Presence and capacity-related institution problem Presence-related interaction problem	SF2: Knowledge creation SF3: Knowledge diffusion SF5: Market formation
	Grid uncertainty	Presence-related interaction problem Capacity-related infrastructure problem	SF3: Knowledge diffusion SF5: Market formation
	Regulatory uncertainty	Presence and capacity-related institution problem Presence-related interaction problem	SF3: Knowledge diffusion. SF4: Providing Directionality

The causes of the *incalculability of financial risk into the market* price of LHC products are primarily connected to market formation. The aforementioned lack of policy and willingness to pay for sustainable goods strongly affect the formation of market demand for LHC products. For the second barrier, *the infeasible business case for e-cracking*, the causes relate to five different system functions. These are Entrepreneurial activities, knowledge creation, knowledge diffusion, market formation and resource allocation. A lack of e-cracking experience through entrepreneurial activities, knowledge creation, and enormous amounts of resources which are difficult to mobilise, cause e-cracking to remain expensive. This is further made difficult by the limited knowledge diffusion in this industry, while the lack of policy and market further decrease its competitiveness compared to conventional cracking. *E-cracking is not included in the grid expansion plans* because of knowledge creation, diffusion, and resource allocation problems. The grid requirements remain unknown, while the stalemate between grid operators and the industry continues without enough communication and cooperation, further limited by the lack of resources for grid expansion. The following two barriers share some common causes. The problems causing *the insufficient communication channels* and the *limited cooperation* are related to knowledge diffusion and the creation and withdrawal of legitimacy. The mission currently lacks legitimacy to encourage the system to create communication channels and partnerships, limiting the knowledge diffusion. Additionally, problems causing the lack of communication channels are related to resource mobilisation, as actors do not have the human or material resources to facilitate this. Sixth, there are *the rapidly changing regulations*. The problems causing this barrier relate to knowledge diffusion and reflexive governance in the system. Regulations are currently in constant flux as policymakers catch up to developments in the system, but not enough knowledge is being diffused to facilitate this. The lack of knowledge diffusion also affects the industry's capacity to anticipate and adjust to policy. Finally, there is the *general uncertainty*. As mentioned, this barrier finds its roots in the other central barriers. The functions it relates to are therefore also closely connected with the other central barriers, with knowledge creation, knowledge diffusion, and market formation taking the most central role. This uncertainty, combined with the risk-averse nature of the LHC industry, has the effect that e-cracking investment decisions get delayed or cancelled, resulting in a strong negative impact on entrepreneurial activities.

This analysis has shown that the system barriers affect the knowledge diffusion function in this system the most, followed by market formation and destabilisation, knowledge creation, creation and withdrawal of legitimacy and resource allocation. Combining this knowledge with the insights from the system problem type analysis shows what problem types cause negative effects to which system function. The troubled *knowledge diffusion* is caused most often by institution related problems, infrastructure problems, and sometimes interaction problems. The problems affecting *market formation* are related to both hard and soft institutions. *Knowledge creation* problems in the system primarily stem from interaction problems and actor problems, while the problems *affecting the creation and withdrawal of legitimacy* find their roots in soft institutional problems. Finally, problems in *resource allocation* stem from barriers related to actor and soft institutional problems.

Keeping the relationships between the functions and the barriers in mind when proposing solutions should ensure that the solutions positively affect the system performance. Targeting certain problem types and system functions should lead to the strongest impact on system performance.

6. Discussion

This research investigated how the implementation of e-cracking could be accelerated by discovering and analysing barriers inhibiting this implementation. This section discusses the implications of this research on the theory and the limitations it experienced. Additionally, new avenues for future research have been discussed.

This research furthered development of the MIS framework. The paper has shown how the MIS framework can be applied in a system primarily occupied by an incumbent, rigid, competitive regime. From this research, it has become clear that knowledge diffusion takes a crucial role in such a system. Industries that were not very dependent on other actors in the past may not have the communication channels to efficiently distribute information to actors they now depend on, such as grid operators. This should be kept in mind when analysing industries that suddenly rely on actors they are not familiar with. Furthermore, this thesis has used the MIS framework in a system where the focus lies on a single technological solution to complete a mission. Taking inspiration from the TIS framework while still considering the context of the broader MIS has proven very valuable in exploring this system. Having one focal technology in the context of a MIS is still a novel concept, and this research has formed a basis to analyse such a system. The effects of the focus on one technology in sustainable transitions should be investigated further, to see if there are benefits a MIS to converging on one technology. Furthermore, this paper has shown how the system functions can be used retrospectively to help design solutions for the system barriers. This method provides an alternative to the use of indicators and function scoring, instead taking a more qualitative approach to understanding the effect of barriers within the system context. To further support this approach, this paper shows how the TIS problem types can be used in the MIS as a means to gain an understanding of what solutions need to bring to the system. Future research could focus on investigating potential correlations between certain problem types and MIS system functions. Finally, this paper proposes the idea of a guiding, cooperating factor in the form of a coordinating unit to guide the innovation system to a swifter transition. Given the support shown by industry actors, the LHC industry could prove to be an exciting study on the effectiveness of such a coordinating entity and the role a guiding factor can play in innovation system literature.

There were some limitations inhibiting the research process. First of all, the limited interview time and correspondence after interviews meant there was no time to gather the data to score the system functions. Additionally, due to the closed nature of the industry, the respondents were opposed to recording and transcribing the interviews, meaning potentially useful data might have been lost. However, the strong focus on finding barriers ensured that this research contributed to accelerating the transition towards e-cracking in the Dutch LHC industry.

7. Conclusion and recommendations

Through this MIS analysis, it has become clear what barriers are present in the system, and how they affect the system performance. Seven central barriers have been identified in this research, namely the incalculability of financial risk into the market price, the infeasible business case for e-cracking, uncertainty regarding grid expansions, insufficient communication channels, limited cooperation, and general uncertainty. Now that it is clear what is missing in the system, the research question can be answered. To answer the question *"What systemic barriers are present in the implementation of e-crackers in the Dutch hydrocarbon sector and how can (mission) governance be improved to overcome these barriers?",* targeted recommendations have been made. These solutions aim to solve the causes of the systemic barriers and, in turn, improve the performance of the innovation system, so that the mission to have a net-zero industrial heat system in the Dutch LHC sector by 2050 may be achieved.

The first recommendation to achieve this is the introduction of protective policy for sustainable cracking products. One such policy may be a blending obligation, where a certain percentage of all olefins or high-value chemicals must be produced in net-zero carbon production processes, like e-cracking. This would reinforce the currently lacking market formation and destabilisation by creating demand for e-cracking products while also decreasing the demand for fossil fuel-fired cracking. An additional tax could be implemented for non-sustainable LHC products that do not meet the blending obligation, further destabilising the market for conventional cracking. At the same time, the price of e-cracking becomes more competitive. Such a policy would have to be implemented at a European level to ensure that the competitive position of petrochemical firms active in the Netherlands is not damaged. Without this tax, conventional HVCs would get imported from countries with fewer regulations, as they would likely be cheaper there. This is also in the national interest of the Netherlands, as maintaining a strong chemical industry is essential for its global competitive position (Znidarsic, 2023). This way, global competition does not further damage the profitability of sustainable cracking. LHC products can become more expensive to reflect the financial risks, while still being a preferred alternative to conventional cracking. This would resolve the presence and capacity institution problems that limited the market formation of e-cracking. As a result, the business case for e-cracking would be bolstered, reducing the financial risk.

The second recommendation is the introduction of a coordinating entity to oversee the transition towards e-cracking. This entity would be an independent actor tasked with tracking mission progress and monitoring what knowledge and resources are required to achieve the mission. It keeps track of what knowledge and resources are present in which parts of the system, and where these can be used. That way, the entity knows who can help each other and can encourage them to do so. The entity can then put relevant actors in contact with each other and help them communicate their needs and knowledge. It would form the bridge between the government, the industry and the research sector. To do this, this entity needs to be an independent actor with strong ties to the different levels of the MIS. One potential candidate for this role is TNO, an independent research organisation that aims to drive innovation through research and collaboration (Znidarsic, 2023). Formalising this role would enable them to do this more efficiently and with more cooperation from the industry. Through this solution, the interaction presence and capacity problems plaguing the knowledge diffusion would be solved, together with the problem regarding the presence of knowledge infrastructure, bolstering the knowledge diffusion in the system. This solution would also facilitate greater resource mobilisation, as the coordinating entity could manage the division of resources. Several interviewees have expressed support for such a coordinating entity, with one mentioning how such an entity should have been introduced much sooner (Interview 7, 8).

The culture in the LHC industry must change to prioritise the mission and collaborate, as we can ill afford to continue working separately. The coordinating unit would encourage this cooperation and a more open attitude within the industry, but increased efforts toward a collaborative mindset would be required. Bolstering collaboration is essential in accelerating the implementation of e-cracking. Increased cooperation would allow actors to share financial burdens while decreasing research and implementation costs, allowing for larger economies of scale in shared projects. This would further bolster the business case for e-cracking by optimising the technology and pooling resources, while reducing the financial risk. Furthermore, cooperation has shown to decrease uncertainty (Fanousse et al., 2019), which currently is one of the central reasons e-cracking projects get delayed or cancelled. As mentioned, this lack of cooperation is caused by a capacity-related soft institution problem, where the current culture in the system does not prioritise the mission or working together. To facilitate this cultural change, the industry should take a more open stance towards working together and prioritise achieving the mission despite the lessened competitive advantage they might gain. Examples of this can be taken from the removal of lead and cadmium in the European PVC industry (Znidarsic, 2024), or the global effort to reduce damage to the ozone layer (World Meteorological Organization (WMO, 2022). In both these cases, the respective industries decided to work together to achieve the mission, and both of them remained competitive afterwards. To further help achieve this cooperative attitude, the coordinating unit can play a central role with other intermediary organisations. They can form the bridge between the actors that otherwise would not cooperate, and help bolster the creation of legitimacy of the climate problem. If this proves insufficient, the government could provide further incentives to encourage (cooperative) projects through fiscal advantages or easier access to permits to further help the industry prioritise the mission. Other than creating legitimacy, achieving this cooperative attitude would affect several other system functions as well. A more cooperative attitude would solve the soft institutional problems that currently negatively affect several system functions. More cooperative projects and research can be done, leading to more entrepreneurial activities and knowledge creation, which are central to making e-cracking cheaper through development. Furthermore, a more cooperative attitude would reinforce the effects of the coordinating unit, as actors would be more willing to participate. This would result in further positive effects on knowledge diffusion and resource mobilisation.

Besides changing how actors interact in the system, it is also essential to ensure there is a physical place where e-cracking projects can be conducted. The coordinating entity should help ensure that grid operators become aware of the grid requirements of the LHC industry, although this would not solve the lack of materials for further grid expansion. The LHC industry will require between 400 to 600 MW per cracking installation (Interview 7), and decarbonising the entire chemistry cluster is estimated to require 70 TWh per year, according to one of the interviewed experts (Interview 8). This makes expanding the electricity grid a high priority on a national level, hence the fourth recommendation is for the government to invest in and encourage an increase in the production of resources used for grid expansion. Increasing the availability of these resources would help solve the capacity-related infrastructure problem currently causing the uncertainty surrounding grid availability and negatively affecting the market formation. It does this by bolstering the resource mobilisation for grid expansion in the system. Once grid availability becomes more certain, the uncertainty surrounding e-cracking will also decrease further.

With these recommendations, e-cracker implementation in the Dutch LHC sector can be accelerated, and the mission to have a carbon-neutral industrial heat system can be achieved.

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Appendix I: Interview guide

Korte introductie wat het VNCI wil, gevolgd door een korte introductie over scriptie
informed consent vragen of informatie gebruikt mag worden in het onderzoek

Introducerende vraag:
Hoe zou u zeggen dat de implementatie van e-crackers ervoor staat?

- Huidige situatie schets
- Komen misschien al wat struikelblokken naar voren

Wat is er nog nodig om deze implementatie te voltooien?

- Versnellen, hudig systeem = probleem (timeline etc)

Waarom is dit er nog niet?

- Antwoord wss surface redenen
    - Doorvragen naar de root causes
    - Vragen naar wat er nodig is en waarom

Om verdere barrières te vinden:

Wat voor andere belemmeringen zijn er die e-cracker implementatie in de weg zitten?

- Eerder gevonden barriers checken/aandragen
- Voorbeeld: Merk je dat er genoeg kennis uitgewisseld wordt over het implementeren over e-crackers
    - Waarom wel/niet
    - Wat voor effect zou het hebben om dit wel te doen
    - Wat is er nodig om mensen te overtuigen om dit te gaan doen
    - Waarom is dit er niet

Appendix II: Interview notes

Interview 1: VNCI

Datum: 18-4-2023
Plaats: Teams
Meeting notes
Hoe kunnen we sneller en scherper innoveren in de chemie industrie.
Hoe ziet het systeem eruit en hoe moet dit verbeterd worden om doelen te halen.

Elektrificeren, Kraken. Stoomkrakers.
Hoe kan e-cracker technologie ontwikkeling versnelt worden.

3 feedstock stromen. CCU, Biobased/photosynthesis, chemische of mechanische recycling

Confirm question is **Hoe kan e-cracker technologie implementatie versnelt worden?**
Ja en de implementatie

Eerst situatie schetsen en vinden wat er niet in het systeem klopt

Ook met ambtenaren spreken
Toegankelijkheid groene stroom ook probleem
Technologie is er op zich wel, alleen de implementatie loopt te langzaam. Volgens roadmap gaan we de deadlines niet halen.
Kunnen we technology developers bereiken?

Europe grootste kans e-cracker
E-kraker werd eerst onmogelijk gedacht, maar toen bleek het opeens mogelijk te zijn. Heel recentelijk enorm aan het opkomen geweest.
Europa focust op e-kraker, Amerika op waterstof, Midden oosten op CCS
China loopt vast, instabiel

Strategisch perspectief

Industrie is vrij gesloten. Praten niet met elkaar. Heel erg competitief en werken weinig samen.

Elektrisch kraken is nog heel duur, duurder dan ouderwets kraken. Onderaan de streep niet gewenst.

Houden hierom liever oude krakers zo lang mogelijk in stand. Onzekere investering

Interview 2: TNO

Datum 08-05-2023
Plaats: Den haag
Geen bereidheid om samen te werken/kennis uit te wisselen

- Tussen petrochemische bedrijven
- Tussen petchem en EPC (kraker ontwikkelaars) buiten pilot projecten om
    - Voornamelijk geldkwestie, ze kunnen er meer geld mee verdienen dan concurrent
- Wel binnen consortia kennisuitwisseling
    - Ook uni Gent centraal binnen dit ivm uitgebreide kraakkennis

Consument geen bereidheid meer te betalen voor groen alternatief

- Moet market pull komen ipv demand push
- Geen bewustzijn over waarde van mileuvoordeel
- Vooral gefocust op geld

Onduidelijkheid zorgt voor vertraging beslissingneming

- Regelgeving van de toekomst is onzeker
- Bedrijven zetten in op meer dan 1 paard om niet verkeerd te zitten
- Verschillende e-cracker technologie
- Onzekerheid business case

Grote investeringskosten belemmeren e-cracker implementatie

- Weinig nieuwe krakers in europa
- Bestaande kraker vloot het liefst operationeel houden ivm miljarden kosten
- Oplossing voor retrofitting is erg handig
- Businesscase is nog niet daar. Het is nog te duur – Wel beeld om in toekomst ook zonder teveel subsidie rendabel te zijn

Bedrijven zijn wel overtuigd dat e-cracker technologie belangrijk wordt. Legitimiteit dus niet echt een kwestie

- Ze maken veel groene praatjes maar in de board room gaat het echt vooral om geld
- Investeerders spelen grote rol

Regelgevingverscherping kan versnellen

- Vooral een duidelijke simpele regelgeving met minder loopholes zou dingen versnellen, Huidige ETS systeem ook lastig te meten. Eerder een taks voor ingaande fossiele koolstoffen

Interview 3: EZK 1

Datum 14-06-2023
Plaats: Den Haag

- Kennis: Vinden jullie jezelf vaardig genoeg? Zijn jullie ook in staat om vaardig genoeg te zijn/toegang middelen connecties om kennis op te halen?
  - Als nee, Merken jullie dat dit jullie beleid negatief beïnvloed?
  - Hoe komt dit? Banden tussen EZK en industrie niet goed? Weinig initiatief?
  - Hoe kan het beter?
- Zijn de communicatie kanalen goed genoeg om kennis te delen met jullie en tech leveranciers etc. communicatie verhaal
- Wat zijn andere grote obstakels bij het maken van beleid?
- Visie 2050 en daarvoorbei > kraken we nog? Deindustrialisatie? Netverzwaring.

Vraag energie (aansluitingen) gaat tegenwoordig keer 10 tov vorige jaren
Wind op zee richting 70 GW
Aan de kust is het veel haalbaarder qua netcapaciteit

Chemelot wil het liefst een kabel, want landlocked, kan niet makkelijk afvangen, maar kan het moeilijkst een kabel krijgen.
Plek bepaalt realistisch gezien de mogelijkheden voor decarbonisatie.
Efficient netgebruik blijft komende 10 jaar erg belangrijk

- Flexibiliteit
- Hoeveelheid vraag

Elektrolysecapaciteit is leidend voor hoeveel windenergie van wind
Ze kijken veel naar waar die stroom (flexibel) ingezet kan worden.
Als je zorgt dat er kosten voor het net verdwijnen wordt je beloond, anders hebben ze het minder graag
Nucleair wordt als optie overwogen.

Grootte problemen en oplossingen nog niet duidelijk, hierom regelgeving ook in verandering.

- Meer communicatie nodig

Continue komt nieuwe informatie binnen

Als tennet dingen aanlegt die niet worden gebruikt à Lage efficientie à Straf

- Ontmoedigt onzekere netinvesteringen

Meer actieve rol EZK met welke (net)investeringen goed zijn zou onzekerheid weg kunnen nemen
Efficientie wordt hier vergeleken met andere landen Door ACM

Vroeger keek ACM alleen achteraf of tennet efficient was.

Interview 4: EZK 2

Datum: 14-06-2023
Plaats: Microsoft Teams
Brede introductie vraag over hoe zij de huidige situatie zien

- Communicatie?
    - Binnen overheid
    - Met industrie
    - Kunnen jullie makkelijk bij informatie die jullie nodig hebben om beleid te maken?
        - Hoe beïnvloedt dit het beleid?
- Is er hierdoor voldoende regelgeving?

Notes EZK 2
Vraag van Douwe: Waterstof vs Elektrisch
Wij: elektrisch is duidelijke keuze

Spanning tussen doelen halen en oplossing op tijd verzinnen is herkenbaar
Huidige EU commissie niet te overtuigen over prijspremium groene producten.
Traject om EU op een lijn is heel lang, als 1 land bijna onmogelijk.
Industrie wil ook zekerheid, dus dit allemaal veranderen brengt chaos.

Interview 5: TenneT

Datum 08-06-2023
Plaats: Arnhem
Gesprek tennet aantekeningen Erik

Markontwerp; flexibiliteit en levenszekerheid. Markt data. Inzicht geven marketen.
Heleen Groenenberg – advies wereld; ecofys. Nu industriële flexibiliteit.
George rodenhuis; ACM, jurist. Netbeheer NL. Nu PA tennet, verduurzaming industrie.
Chemelot; modeleren verwachting e vraag. In 2030 aansluiting prima.
Tennet moet het kunnen plannen. Uitvoering en vergunningen. Grote uitdaging vergroten net.

- Vergunningen
- Is er ruimte? Flexibiliteit is goed voor het systeem.
- In de toekomst is een baseload contract veel duurder
- Voor netaansluiting is het: aansluiten meer parten onder voorwaarden op bepaalde piekmomenten afzien van vraag.
- Kan het ook 120%> wat is technisch gezien voor een kraker in een 2050 systeem om nodig te hebben? Meer netkosten "(minder gebruikt, maar stroom goedkoper)
    - Onduidelijkheid binnen tennet over LHC benodigdheden.
- Voorbereiding bepaalde scenario's. Wat neem je mee.
- Technische aansluitn gmaakt het uit wat je aan infrastructuur wilt gaan bouwen, systeem niveau kust is anders dan achterland.

Visie bedrijven > innovatie e crackers
Ik dacht flexibiliteit.

- Aanleg kabels: main bottleneckts=
- Beschikbaarheid grondstoffen > 2 kabelbedrijven uitverkocht.
- Overal exponentiele groei materialen.
- Vergunningen; trace ontwikkelen = heel veel tijd
- Ruimte : substations

Informatie voorzieningen.

Aantekeningen Tennet Stan

Tennet geeft niets om waar stroom voor gebruikt wordt.
Stel er wordt hun verteld om aansluitingen aan te leggen, dan gaan ze er mee aan de gang

Ze maken investeringsplannen, het liefst 10 jaar vooruit. Aannames, scenario's. Om te identificeren wat er mogelijk is en waar vergunningen voor te krijgen zijn.

Kwestie dat het net niet overal vergroot kan worden.

Huidig plan is terugredeneren van een volledig duurzaam scenario in 2050
Discussies die hier spelen is angst dat er een super dikke kabel wordt gelegd en dat bedrijven later het niet willen gebruiken en weggaan. Dat het niet gebruikt gaat worden.
Ze hebben goeie info nodig over wat industrie nodig heeft (aannemend dat ze doorgaan). Bedrijven investeringsplan laten zien zodat ze weten wat er komende 10 jaar aankomt (en wat niet).
Door stikstof en andere vergunningen wordt het soms moeilijk om net aan te leggen.

Steeds ambitieuzere plannen, moeilijk te electrificeren.
In de basis zien ze dat zon en wind de grootste levering wordt. Inconsistente vraag. Maar sommige vraag kan niet flexibel ingericht worden.
Als je flexibiliteit kan inbouwen, doe dat. Belangrijk om te weten als dat niet kan. Is op het moment nog niet duidelijk.
Flexibiliteit zorgt ervoor dat je eerder met je fabriek aan de gang kan.
Overcapaciteit wordt ook gewaardeerd om weer extra stroom af te nemen.
Belangrijk in netplanning als bedrijven die overcapaciteit willen installeren. 1.2 ipv 1 GW.
In nederland afzetmarkt die een beetje meer wil betalen voor een duurzaam product.

Nederland gunstig omdat kraken al gebeurt hier. Bekend in het ecosysteem.

Vraag van gigawat e-crackers mogelijk nog niet meegenomen in bestaande scenario's

Comminucatie tussen TenneT en industrie is bestaat wel. Informatie is alleen nog niet heel concreet.
Is nog niet bekend hoeveel gigawatt capaciteit industrie wil hebben.
Bedrijven in terneuzen kunnen CCS, dus investeren daar ook in en willen later pas electrificeren.
Bedrijven die dit niet kunnen mikken sneller op electrificatie.
Vraag aan de kust is gunstig voor het systeem. Dan hoeft het niet het net op in het land.
Niet alleen de uitslating, maar ook het net dat tussen opwekking en gebruik ligt.

Beschikbaarheid kabels, personeel, geld, vergunningen. Iedereen wil exponentiele groei maar productiecapaciteit blijft laag. Kabelboeren leeggekocht. Ook paniek, maar ook hoop dat er meer in geinvesteerd wordt. Vergunningstrajecten wordt ook lastig. Ruimte. Substations zijn ook groot.
Tennet wil gestructureerd informatie binnenkrijgen. De bedrijven die volgen niet dezelfde structuur van informatie geven. à Fix te informatievoorziening. Dat iedereen hetzelfde doet

Interview 6: Large interview actor 1

Datum: 30-05-2023
Plaats: Teams

Is het innovatie systeem nu inlijn met de steilheid die we nu doormaken in 2050?
In november pilot plant operationeel.
Hierna vrij snel stappen maken om het up te scalen.
Voor 2030 sws een fornuis 100% electrisch
Risico's:
Technisch

- Onderzoek voor doen

Infrastructuur eromheen

- Electriciteitsnet
- Geen stoom overschot dus extra elektriciteit, 600-700 MW nodig voor kleine kraker

Moet kritisch bewijs leveren dat technologie werkt.

- Plan is voor 2030

De businesscase moet ook positief zijn. Zit wel in de buurt maar nog kleine push nodig

- market pull nodig (ziet er atm best wel goed uit)
- Subsidie zit atm wel goed

Elektriciteit is best prijzig. Businesscase rondkrijgen door CO2 efficient krijgen, maar marktpremium ook nodig. Markt is best bereid om meer te betalen, vooral de brands. Ze willen scope 3 verminderen en daar is duurzame plastic nodig.
Fossiel wordt nog niet voldoende gedestimuleert. Al helemaal niet globaal.
Europese wetgeving moet streng zijn mbt welke producten geimporteerd mogen worden want anders worden ze eruit geconcurreerd.
Best wel wetgeving die recycling stimuleert, verwacht dat meer wetgeving eraan gaat komen.
Durft niet met zekerheid te zeggen of wetgevers up to date genoeg zijn om wetgeving te maken.

Heel veel onzekerheid over waar ze heen willen, capture, electrisch, H2

- Onbewezen technologien
- Meest bewezen (capture) niet gunstig op lange termijn
- Electrisch beste lange termijn, waar gaat dan restgas heen?
    - Valorizeren

Massabalans qua gassen kunnen berekent worden

Technologie bewijzen ligt bij de industrie

- Ze willen data voor de volgende stap gaan maken
- 2023-2027 minimale traject
- Dataverzameling kost tijd.

Zekerheid enorm belangrijk ivm hele grote investering
Vooral samenwerken met Linde wat alles enorm versnelt
Co eigenaar technologie uiteindelijk
Steun voor de-risken zou het versnellen. Eerst niet gekregen.

Als je bouwt, stikstofregelingen en vergunningen.

- Moet wat sneller en coulanter

Teruggehouden worden door de overheid ivm stikstof enzo kan als risico worden gezien.
Moet navragen of duidelijkheid er voldoende is over toekomstig beleid.
Waarom europa/nederland?

- Verhouding gas/electriciteit prijs
- Visie van de regio

Businessmanager vision

- Real challange: Grid availability. In NL big issue because of grid congestion
- Electricity price vs fossil fuel
- Prijs fossiele producten vs duurzaam

Het niet doen pakt slechter uit dan het wel doen

Interview 7: Large interview actor 2

Datum 11-08-2023
Plaats: Microsoft Teams

Kennismaking

Very integrated process. Dingen aanpassen leidt tot verandering verhoudingen en daardoor problemen down the chain.
Wat heel erg nodig is is zekerheid.
Businessdevelopment **wil graag weten binnen welke randvoorwaarden zij moeten werken. -> Consistent beleid. Die ontbreekt nu. à moeilijk te bereiken.**
Regelgeving verandert snel, maar besluitvorming is traag. En trage besluitvorming vanwege conflicterende belangen. Wat beleidmatig nodig is kan politiek geen draagvlak vinden.
Markt moet het dus zelf doen, beschikbaarheid power, technologie, etc. Komt een turning point waar bijv power goedkoop beschikbaar is.
Bedrijf heeft analyse met welke randvoorwaarde nodig is.
Partijen (overheid, industrie, TSO) **moeten samenwerken**, en wat moeten die partijen technisch invullen om te functioneren.
Het wordt een heel ander domein als je gaat electrificeren, want de hele waardeketen, en dus partijen die betrokken zijn veranderen.
Problemen worden steeds meer hoe dieper je gaat kijken. **Bijvoorbeeld dat de transformer markt helemaal vol zit**. Kan je nergens krijgen. Elektriciteit is de meest pure vorm van energie, dus hiermee verwarmen is het meest efficient

Oplossing: Veel meer overleg.
Mensen komen er niet aan toe, **weten niet of het hun rol is.**
Voorheen was het ook nog niet bekent dat dit uberhaupt mogelijk was. Veel partijen caught off guard en zijn er niet genoeg bewust van hoe dicht bij het is --> PRAAT MET ELKAAR

De directe electrificatie decarbonizatie route is betrekkelijk laat op gang gekomen. Dit omdat het in het verleden voor onmogelijk werd gehouden.

Zodoende moeten veel van de kennis netwerken en probleemstellingen nog vorm krijgen. Het is dan ook een prachtige oppertunity voor Nederland hierin voorop te lopen.

[in reactie op voorstel coordinerende eenheid]
Ik denk dat dit een belangrijk punt is. Er moet nog veel gepraat worden om de uitdagingen voor iedereen scherper en scherper in beeld te krijgen en daar vervolgens plannen en beleid tegenaan te zetten. Goed om een orde grote aan te geven. Zoiets als continue **400 tot 600 MW** per craker complex.

Interview 8: Large interview actor 3

Datum: 11-05-2023
Plaats: Teams

Waarom cracker of the future niet gelukt?
Kennisuitwisseling met Uni gent

* Large interview actor 3: waarom überhaupt investeren in e-crackers?
Pilot bezig
Vragen naar view over bestaande barriers gevonden in gesprek met TNO?

- Hoe beïnvloedt de gelimiteerde kennisuitwisseling over dit onderwerp tussen producenten de implementatie van de technologie
- Gebrek aan market pull voor duurzaam alternatief kraken. Consument wilt niet meer betalen
- Maakt onzekerheid over toekomstige regelgeving implementatie lastiger?

Je kraakt nog steeds > flue gas blijft over. > hier moet je wat mee doen > geen probleem (verboundsysteem) interesse koolstof valoriseren > chemicalien
Als samenwerking wordt een pilotproject vruchtbaar
Bedrijven wedden op meerdere paarden
Van regio tot regio verschilt welke decarbonisatie oplossing nuttig is

- Geen globale oplossing
  - Infrastructuur, prijs, groene energiebeschikbaarheid, etc.
- **70 TWH om cluster van groene stroom te voorzien (ongeveer verbruik van belgië)**

PCF ethyleen onder bepaalde waarde (product carbon footprint) = nodig (global markt maakt dit lastig) , CBAM proberen ze t te fixen maar vraag is of het werkt..
Europese systeem beschermen wordt vrijwel praktisch onmogelijk. Het is een globale markt.

Hier moeten we meer nadruk leggen op de challenge die we hebben voor het maken van de chemische bouwstenen (commodity chemicals), waar we over een globale markt praten en waar veranderingen met veel kapitaal en onzekerheden verbonden zijn, die door de natuur van commodities een uitdaging vormen...

Je moet op EU regulatie en nationale regulatie anticiperen
VRAAG: Is (toekomstige) regulatie atm duidelijk genoeg om te anticiperen?

- **Veel in beweging, veel voorstellen. Allemaal hebben impact op beslissing e-furnace. ATM veel aan het leren waardoor nieuwe discussie voortbloeit**
- **Nieuw terrein. Veel dingen veranderen tegelijk.** Hierdoor lopen dingen bij mensen die regulering maken weten niet gelijk op. Zorgt dat het trager verloopt. Te snelle wetgeving sluit goeie technologie uit soms.
- In europa caren ze om hoe low carbon footprint wordt bereikt e.g. per se groene waterstof. Dus subsidies alleen voor dat.

Wordt in de markt ethyleen met kleinere carbon footprint meer gewaardeerd dan met een grotere carbon footprint? Niet genoeg
Echt toegang nodig tot groene energie

- Daarom ook meedoen aan tenders voor windmolenparken

Je moet ook kijken wat is sociaal verdraaglijk. Je moet niet zo snel electrificeren dat energie voor huishoudens onbetaalbaar wordt.
Stroomprijs is atm nog affhankelijk van fossiel
Moet naar onafhankelijk
Hoe verschuif je coordinaten

1. Crises
2. Dictatorschap
3. Inspirerend Leiderschap

Zitten atm in een lastige fase omdat de coordinaten nog niet zijn veranderd

- Nog geen overvloed van groene elektriciteit enzo

Basis producten kan je nog wel managen, maar met afgeleiden word het lastig. > model toch meer voor Eu markt producren (CBAM). Welke groei zit dan weer hier..
Olifinen globale markt. Hoe veranderd dit de competitivness.
Ander verhaal PCF druk bezig systeem alle 45k producren de PCF berekenen. Proactief kijken of ze logica bij andere kunnen implementeren.
LCA standardisatie

Anticiperen op Eu regulatie > is die regeling duidelijk genoeg? Er is veel in beweging. Veel voorstellen voor regulering. Hier kijken wat het betekend > feedback geven > dan deze consequenties.
REDIII klassiek voorbeeld.
Allemaal besligging impact e furnace
Er word ook veel geleerd > als je er mee bezig gaat houden.
Wat er nu gebeurd is zo veel, nog nooit gezien. Politiek en wetgevers en industrie loopt nu niet kwa kennis en mogelijkheden niet gelijk op.
Verschil kennis beleidsmakers > asymetrische kennis : blemmert beslissingen regelgeving.
VS: maakt niet uit hoe je H2 maakt zoalng maar CO2 footprint lager dan ..
EU: moet groen > elecstrolyse.
Toegang nodig naar goedkope groene energie.
Maar als EU te vroege goals zet dan andere technologiën overwegen → CCS om doelen op tijd te halen
Wanneer gaat het coordinaten systeem verschuiven > niet terug kijken > niet vooruit (kosten perspectief)

- Crisis
- Streng leiderschap
- Inspirerend leiderschap / kracht kennis en techologie sluiten

Stroomprijs = Merit order > verbonden fosiel stroomprijs > hier moeten we vanaf
Zoeken painpoints > electficiereing algemeen
Hoe zien jullie electrificering? Efficientie? Stroom direct gebruiken? Of voor moleculen? Meer stappen > terugvormen.. afweging = hoe ga je efficient groen stroom (komende 10 jaar nog een gelimiteerd goed) gebruiken?

Lastrige fase: we zijn nog niert getranfsomeerd > dilemma wat doen wemet groene stroom, efficine tomgaan > electricieren.

e-furnance en e cracker is anders > e drives veel efficienter dan steam drive

Als richtlijn kun je stellen, dat een state-of-art stoomkraker (1 miljoen ton ethylen) tussen de 2 en 3 miljard euro kost (in EU).

[In response to the risk averse nature of the industry]

- Risicomijdend, want veranderingen betekent automatisch kapitaal zeer intensieve investeringen die zich niet terugverdienen o.b.v. huidige economische klimaat

- Kortetermijnwinst niet altijd primair doel, maar creëren van shareholder value is wel een thema dat nog wel eens conflicteert met bold investments.

Geen specifiek e-cracker probleem maar algemeen energy transition probleem

[their reflections on our solutions to this conundrum]
Oplossingen moeten inderdaad nog wel verder uitgewerkt worden.:

- risico's/onzekerheden verminderen of aanvaarden is een redelijk open deur waar je nog alle kanten mee op kunt

- Betere communicatie tussen overheid/bedrijven/netbeheer lijkt me wel essentieel. Een coordinerende eenheid is in mijn ogen iets wat eigenlijk al jaren geleden had moeten zijn opgericht aangezien al wel duidelijk was dat er op gebied van electrificatie van alles zou moeten gaan gebeuren om 2030/2050 targets te halen.

Interview 9: Large interview actor 4

Datum: 16-07-2023

Brede vraag hun beeld van de situatie
Wat voor beren zien zij op de weg?
Bevestigen barrieres die wij tegen komen

- Hoe zien zij communicatie met de overheid
  - Zijn ze open om te praten over beleid?
  - Loopt communicatie soepel?
  - Laat de overheid ook weten wat zij van de industrie willen weten?
- Hoe zien zij communicatie met netbeheer
- Is deze communicatie voldoende?
- Kunnen zij de nodige informatie vinden qua regelgeving (zowel huidige als toekomstige)

- Hoe beïnvloedt de regelgeving jullie implementatie van de e-cracker
  - Sneller/langzamer
  - Houdt het ook dingen tegen?
- Zijn er genoeg middelen (geld/materiaal/mensen) om dit te implementeren

Wat is er nog nodig voordat de e-cracker er staat

Notes
Denktank
Waar moeten we naartoe, hoe gaan we daar komen
Team met brede achtergrond, ook overheids-links
Interviewee is betrokken geweest bij de Innovation council
2 dingen drijven verandering

- De pot met goud aan het einde van de regenboog (concurrentiegevoelig)
  - Wat je hebt is goed, maar het kan beter
- Burning platform (samenwerking want groter extern probleem)
  - Veel urgenter. Vervelende situatie en we moeten weg

Probleem is dat klimaatverandering niet gezien wordt, omdat het constant gemeten wordt, langzamer proces. Mens kan hierdoor minder goed op reageren. We reageren traag op trage verandering.

In eerste instantie gaat het in een bedrijf vaak om je positie te handhaven door je relatieve positie te verbeteren en voldoende winst te blijven maken om te overleven. Bedrijven zijn wat dat betreft net organismes.

Kan wel opgelost, zoals bij de Ozonlaag
Hoopten dat Parijs 2015 ook een goede aanleiding was om naar burning platform mentaliteit te gaan
Vraag: Gaan we het molecuul uit de kraker nog nodig hebben? Ja.
Hoe kan ik het anders maken? Wel andere routes maar niet zo efficient/schaalbaar als kraken.
Elektrificatie, mooi want je kan aanhaken bij duurzame elektriciteit.
Industrie komt langzamerhand tot dezelfde conclusie
Energie intensiteit is nog een probleem

Groot vermogen op kleine plek
Op het moment nog problemen met gridcapaciteit en die worden traag opgelost. In eerste instantie is dit veroorzaakt door het feit dat de energievraag nier voor de TSO's zichtbaar was. Het huidige proces doet nl. geen beroep op infrastructuur. De energiedrager komt mer de grondstof mee. Het is dus een witte vlek.

Process moet robuust zijn. Juiste moleculen in het juiste bakje. Apparaat wat dit doet is moeilijk te maken.
Is positief dat het gaat lukken.
Economisch: Is stroom competitief met fossiele energie
Je hoopt dat de markt dit compenseert, maar blijkt beperkt waar.
Beleid in de richting van bijmeng helpt. Maar als je in je eentje als bedrijf meer doet, merk je dat dit nog lastig is.
Meer market pull nodig. Level playing field belangrijk. Bijmengverplichting in geheel europa zou gewenst zijn.
Aantekeningen erik:

Interviewee:
Wat drijft innovatie?
De pot met goud – wat je hebt is goed maar waar je naartoe kan is beter? Factoren richten zich nu op pot met goud. Daarnaast heb je een learning platform; vervelende situatie en we moeten er van weg.

1. Eerste zijn = concurrentie gevoelig
2. Samen werken want bedreiging buiten ons

Pobleem klimaat verandering = lastig proces. Lastig voor maatschappij om hier op te reageren want traage verandering.
Resource barriers:

- Technologische barriers
    - Hoeveelheiden aan groene stroom. Die er niet zijn. Opwekken – transporteren – gebruiken.
    - Machine bouwen waar je die elektriciteit kan toepassen. Uitdaging zit in energie intensiteit van het proces; niet het vermogen maar vermogen op een klein eplek. Bijzonder materiaal eisen. Dit is de uitdaging. Proces moet ook robuust zijn. Ook de mechanische eisen. Alles bij elkaar maakt het uitdagend.
- Economische barrieres
    - Is de stroom competitief met de huidige manier van verwarming.
    - PKosten door de markt duwen – lastig: moet gefaciliteeerd worden door beleid (bijmeng verplichting). Markt pull crieeren. = normeren. Moet voor iedereen gelden. Wel op EU niveau. Onze ligging is super. Door export importeren we geld.

Socio institutionele barrierrs

- Maatschappelijk debad: is de stroom er? Voor markt adsobtie. Zijn er markt paertijen die de stroom kunnen en willen keveren? Wind zon/ beetje nuclear.

Regelgeving. Scope 1. Lost niet he.

E crackers; vraag gaan we het molecuul nodig hebben ? ja.
Hoe doe je dat
Beleid
Spanning tussen doelen en oplossingen – hier is geen oplossing.