Strategies for Overcoming Barriers in the Biomass-to-Syngas Value Chain: A Solution-focused Approach in the Context of the Dutch Bio-based Chemical Sector

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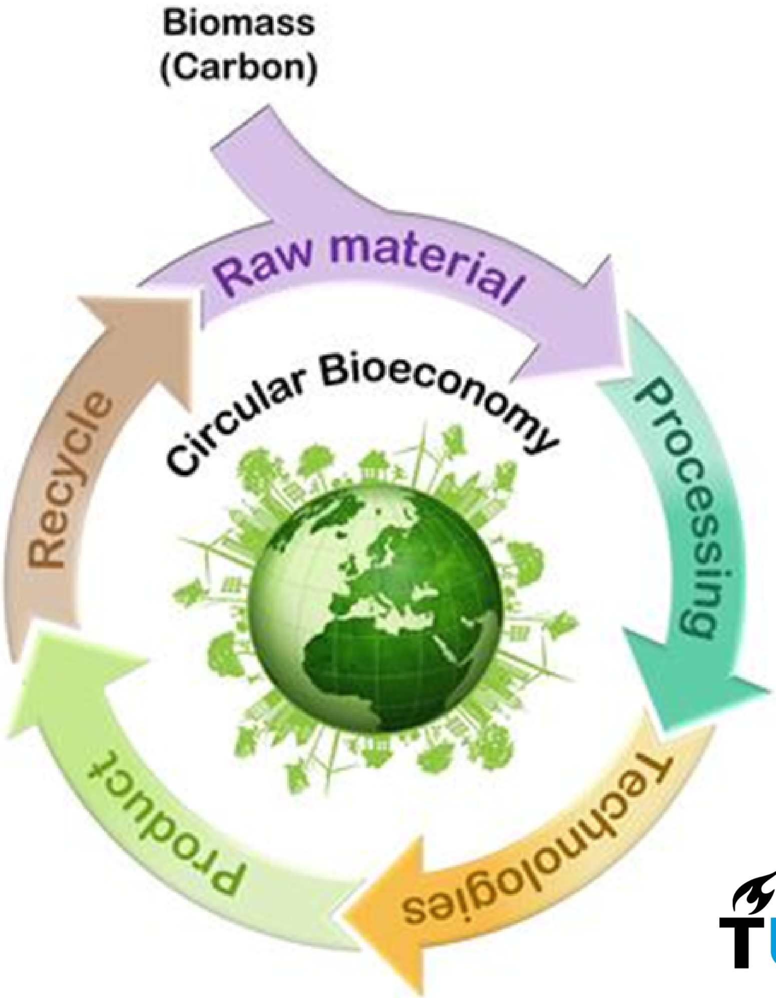
Tom Lammers



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Strategies for Overcoming Barriers in the Biomass-to-Syngas Value Chain: A Solution-focused Approach in the Context of the Dutch Bio-based Chemical Sector

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Abstract

Over the past decades, global efforts have been made to address climate change and improve the well-being of our planet. The European Union (EU) has set ambitious greenhouse gas (GHG) emission reduction targets and strategies to combat climate change. Bio-energy, specifically biofuels produced from biomass, has gained significant attention as a crucial component in decarbonizing energy and production systems. While renewable energy sources like solar and wind are primarily used for electricity generation, bio-based processes focus on producing biofuels for heat, power, transportation, and biochemistry sectors. Therefore, biomass can play a crucial role in decarbonizing hard-to-abate industries that are challenging to electrify, such as the chemical industry, heavy road transport, and marine and aviation sectors. However, the chemical industry, a major energy consumer and emitter of CO2, relies heavily on fossil fuels as feedstock and energy sources, necessitating a shift to carbon-free alternatives.

The biomass-to-syngas pathway, which involves converting biomass into bio-based syngas through gasification, has emerged as a promising solution for a more sustainable chemical industry. However, the development of this value chain faces technical and commercial challenges. Technical challenges include tar formation and product impurities, while commercial challenges include financing limitations, low market maturity, and sustainable feedstock availability. Moreover, handling and using biomass as a feedstock itself present constraints such as transportation limitations, variable composition and properties, low energy density, and high moisture and oxygen content. These challenges hinder the competitiveness of bio-based syngas production against fossil fuel alternatives and impede the development of the biomass-to-syngas value chain.

To address these challenges, the integration of torrefaction technology into the value chain has been proposed as a promising approach. Torrefaction enhances biomass densification, reduces moisture content, and improves the overall viability of the biomass-to-syngas value chain. However, the commercial implementation and economic feasibility of torrefaction remain uncertain. Additionally, research primarily focuses on technological improvements and lacks a deeper understanding of system integration, practical implementations, and stakeholder perspectives.

This research aims to bridge these knowledge gaps by actively engaging with stakeholders across the value chain to address the challenges of developing the biomass-to-syngas value chain and propose comprehensive solutions through stakeholder involvement. It explores the system integration of torrefaction technology, considering industry stakeholders' perspectives. The research employs a step-wise approach, focusing on an in-depth case study of the Dutch chemical industry. Data is collected through an exploratory literature review, semi-structured interviews with stakeholders, a questionnaire, and a webinar serving as a panel discussion platform.

The research identifies 44 barriers hindering the development of the biomass-to-syngas value chain and the integration of torrefaction technology. These barriers primarily stem from deficiencies in innovation-specific institutions, network formation and coordination, and the production system. Stakeholders and experts agree that technological and logistical challenges can be overcome. However, addressing failures in innovation-specific institutions, such as the lack of economic and policy incentives and an unfavorable regulatory environment, is crucial for driving the development of the value chain. Based on these findings and insights obtained through expert reflection the research develops comprehensive solution statements and formulates five strategies to address the identified barriers, including cohesive policies, industry-tailored subsidies, standardized certifications and regulations, enhanced network formation, and decentralized torrefaction technology integration.

In conclusion, this research underscores the significance of the biomass-to-syngas pathway as a key driver for a sustainable chemical industry. By addressing technical and commercial challenges and the integration of torrefaction technology, comprehensive strategies have been formulated to overcome barriers and unlock the value chain's full potential. These findings thereby provide actionable insights for policymakers and industry stakeholders to drive the sustainable development of the biomass-to-syngas value chain.

Preface

The completion of this thesis marks a significant milestone in my academic journey. It is the culmination of months of research, analysis, and reflection, and I am honored to present the findings and contributions of this work. However, I would like to express my sincere gratitude to the individuals who have played an instrumental role in the success of this thesis research and my academic journey. Without their invaluable support and assistance, this study would not have been possible.

First and foremost, I would like to express my deepest gratitude to my supervisor, Gijsbert Korevaar, for his guidance, support, and valuable insights throughout the entire process. Gijsbert's expertise in the fields sustainable chemistry and the sustainability assessment has been invaluable in shaping the direction and quality of this research. Additionally i would like to thank Geerten van de Kaa for being part of my graduation committee and providing valuable feedback.

I would also like to extend my appreciation to Patrick Nanninga and the company Uniper for providing me with the necessary resources and a conducive environment for conducting this study. Without their network and knowledge of the sector i would not have been able to obtain the knowledge and insights I did. Subsequently, I want to express my sincere appreciation to the participants and stakeholders who generously dedicated their time and expertise, allowing me to collect the necessary data and gain valuable insights for this research. Their contributions have greatly enhanced the credibility and significance of the findings.

Lastly, I would like to extend my heartfelt gratitude to my parents, who have played an exceptional role in my academic journey. Their unwavering support and encouragement have been invaluable. They have stood by me through every challenge, providing a constant source of motivation and inspiration. I am truly grateful for their belief in me.

Tom Lammers
Rotterdam, August 2023

Executive summary

This executive summary presents a concise summary of the research findings and recommendations derived from the thesis, aimed at managers, policy makers and businesses interested in its valuable insights. The research primarily centers around the advancement of the biomass-to-syngas value chain within the bio-based chemical industry in the Netherlands, with a specific focus on overcoming technical and commercial obstacles that impede its competitiveness. Furthermore, the integration of torrefaction technology into the value chain is explored through an examination of stakeholder perspectives, aiming to enhance the overall viability and sustainability of the system.
The research followed a step-wise approach, focusing on an in-depth case study of the Dutch chemical industry to gain insights into the development of the biomass-to-syngas value chain within this specific context. Through stakeholder interaction and a detailed delineation of the value chain system, the research comprehensively identified 44 interconnected barriers stemming from deficiencies in innovation-specific institutions, production systems, and network formation. Technological and logistical challenges were found to be addressable, while barriers originating from failures in innovation-specific institutions, such as the absence of economic and policy incentives and unfavorable regulations, were prioritized. Building on stakeholder input, existing literature, and expert reflections, the research developed and refined comprehensive solution statements. These statements resulted in five strategies aimed at driving the sustainable development of the biomass-to-syngas value chain. These strategies include cohesive policies, industry-tailored subsidies, uniform certifications and regulations, enhanced network formation and strategic supply chain partnerships, and decentralized integration of torrefaction technology.
From the strategies and research findings several actionable recommendations are derived for promoting the sustainable development of the biomass-to-syngas value chain. These recommendations, which will be discussed below, are targeted at managers and policy makers aiming to enhance the value chain's viability and environmental impact. Additionally, given that the research was conducted during an internship at the company Uniper, specific recommendations have been tailored to Uniper's potential role in the Dutch biomass-to-syngas value chain.

Support institutional collaboration: the research demonstrated that in order to address the failures in innovation-specific institutions, including the absence of economic and policy incentives and an unfavorable regulatory landscape, it is essential to establish industry-tailored subsidies, cohesive EU policies, and uniform certifications and regulations. While governmental parties and policy makers are the main stakeholders responsible for undertaking action in developing these solutions, the research showed that collaboration across the entire value chain is crucial. Therefore, firms and policy makers should collaborate to develop consistent and clear policies and advocate for the development of uniform laws, regulations, and international standards at the EU level. These laws and policies should encompass the international scope of the industry, enhance the sustainability of the chemical sector, and raise awareness among the general public about the potential of biomass. Managers, including those from Uniper, can contribute to these efforts by providing financial support, actively participating in policy discussions, and leveraging their industry expertise. Additionally, supporting the implementation of industry-tailored subsidy schemes can attract investments and mitigate financial risks for gasification projects. Therefore through active lobbying and collaboration with policy makers, industry stakeholders (such as Uniper), can shape a favorable regulatory environment and establish comprehensive and harmonized regulations that support the development of the biomass-to-syngas value chain.

Promote knowledge and awareness & Drive Research and Development: The research revealed a significant lack of knowledge and awareness regarding the sustainability potential of biomass as a feedstock for the Dutch chemical industry, which has resulted in unsupportive policy schemes and limited progress in biomass gasification projects, hampering the development of the value chain. To promote knowledge and awareness and drive research and development in the biomass-to-syngas value chain, industry stakeholders should therefore collaborate and actively engage in educational initiatives, industry events, and public discussions, an example of such an activity would be the webinar that was hosted during this research. Moreover, industry stakeholders and policy makers can participate in forums and working groups facilitated by branch organizations to exchange ideas and stay updated on advancements in biomass-to-syngas technologies and policies. By promoting knowledge and awareness, industry stakeholders can positively influence public perception and policy support for biomass as a sustainable feedstock, creating an environment conducive to the value chain's development in the Dutch chemical industry.

In addition to promoting knowledge and awareness of the sustainability potential of biomass gasification for the production of chemicals, the findings show that active engagement by large chemical firms and investors in the research and development of gasification technology itself is crucial. Fostering partnerships and collaborations with technology providers, research institutions, and other industry players can therefore drive advancements in gasification technologies, leading to significant reductions in emissions and improvements in process optimization. Consequently, large chemical firms and investors can significantly drive the performance and cost-effectiveness of gasification technology by allocating resources to research and development initiatives. Moreover, findings from the expert reflection session highlight that the profitability of gasification projects can be improved by prioritizing large-scale development and the recovery of valuable minerals as by-products in gasification projects. Technology developers should therefore focus on these aspects, while larger firms can provide the necessary financing for scaling up the projects.

Capitalize on torrefaction technology & form strategic partnerships with agri-cultural sector for feedstock supply: Companies operating in biomass trading and asset management, such as Uniper, have a valuable opportunity to leverage torrefaction technology. The research found that by integrating torrefaction into the value chain system in a decentralized manner, these companies can effectively tackle challenges associated with feedstock supply, logistics, and standardization. This strategic implementation of torrefaction holds the potential to enhance the overall performance, profitability, and resilience of the value chain. Hence, through investments in and operations of torrefaction plants, Uniper can play a pivotal role in elevating the performance and standardization of biomass feedstock into a tradable commodity. Thereby contributing significantly to the development of a more efficient and reliable value chain. Moreover, by being the first to invest in the development of torrefaction technology at scale, Uniper can reap first mover advantages such as brand loyalty and technology leadership. For example, Uniper's torrified material could become the industry standard for biomass commoditization, enhancing its competitive advantage. Moreover it allows Uniper to strategically capture feedstock locations.
Furthermore, the research highlights that the integration of torrefaction technology into the value chain not only enhances the performance of gasification processes but also broadens the scope of viable feedstock sources. To ensure long-term feedstock supply for biomass-to-syngas projects, companies should establish strategic partnerships with agricultural players and feedstock suppliers. This enables them to access a more diverse and reliable feedstock supply. Additionally, through these collaborative partnerships, companies can develop sustainable sourcing practices, optimize logistics, and minimize supply chain risks. Therefore, by actively engaging with feedstock suppliers, companies can foster mutually beneficial relationships that contribute to the overall sustainability and success of biomass-to-syngas projects.

In conclusion, this thesis provides valuable insights into the barriers and solutions in the development of the biomass-to-syngas value chain for bio-based chemical production in the Netherlands. The proposed strategies offer a roadmap for driving the value chain's development, increasing sustainability, and promoting growth in the bio-based chemical industry. Additionally, the study sheds light on the integration and role of torrefaction technology within the value chain, providing a deeper understanding of industry perspectives. By expanding the knowledge base in these areas, policymakers, industry stakeholders, and researchers can collaborate to overcome barriers and unlock the full potential of the biomass-to-syngas value chain for sustainable bio-based chemical production.

Contents

List of Figures

List of Tables

List of abbreviations

GHG Greenhouse Gas

R&D Research and development

TIS Technological Innovation System

CBE Circular Bio-economy

EU European Union

BtX Biomass-to-X

FT Fischer-Tropsch

VNCI Koninklijke Vereniging van de Nederlandse Chemische Industrie

SfSA Solution-focused Sustainability Assessment

SfRA Solution-focused Risk Assessment

NGO Non-governmental organisation

SME Small and medium-sized enterprises

TRL Technology Readiness Level

CAPEX Capital Expenditure

OPEX Operational Expenditure

1 Introduction

1.1 Background

The European Union (EU) has set ambitious greenhouse gas (GHG) emission reduction targets and strategies to mitigate climate change impacts. Becoming climate neutral by 2050 will require the deployment of various renewable energy sources [17]. The development of renewable energy is therefore considered as an imperative and essential countermeasure for resource and environment sustainability.
In this regard, bio-energy has received significant attention among other emerging renewable energy technologies such as solar energy, wind energy, geothermal energy, marine energy, and hydropower [44]. Although the use of biomass for energy purposes has been the subject of ongoing debates, it is expected that biomass will make a significant contribution to the decarbonization of energy and production systems in the years ahead [63]. Unlike solar and wind energy, which are primarily used for the generation of electricity, the focus of bio-based processes lies in the production of biofuels that can be applied to heat and power generation, as well as in the transportation and biochemistry sectors [16]. Biomass can therefore play a crucial role in decarbonizing hard-to-abate industries, as not all sectors can feasibly transition to electrifying their production methods [24]. Specifically, the chemical industry, heavy road transport, and the marine and aviation sectors heavily rely on biomass as one of the limited options to substitute their fossil feedstock with renewable resources, thereby GHG's [58]. The chemical industry, in particular, is the largest energy consumer among industrial sectors and ranks third in terms of direct CO2 emissions [53]. This is primarily due to the extensive use of fossil fuels as the primary feedstock for synthesizing final products, with half of the sector's energy input dedicated to this purpose. Given that most chemical end-products inherently contain carbon, achieving a carbon-free chemical industry without carbon-based feedstock therefore poses a significant challenge [23]. Hence, when discussing the chemical industry, the focus should shift from decarbonization to achieving a state of net-zero emissions. This entails not only reducing the energy intensity and emissions of production processes but also addressing the environmental impact of the chemical products themselves. In order to achieve a truly sustainable chemical industry it is therefore necessary to strive for both complete climate neutrality and circularity and find alternatives to the fossil carbon sources used for the production of (basic) chemicals [64]. In this regard scientist such as Rajesh Banu et al. and Stegmann et al. have advocated for the development of biorefineries within the Circular Bio-Economy (CBE) concept. The CBE concept emphasizes the sustainable and efficient utilization of biomass in integrated production chains, such as biorefineries, to maximize its value over time through cascading. It involves the utilization of residues and wastes and aims to optimize the overall resource efficiency in the product chain (See Figure 1) [58] [27].

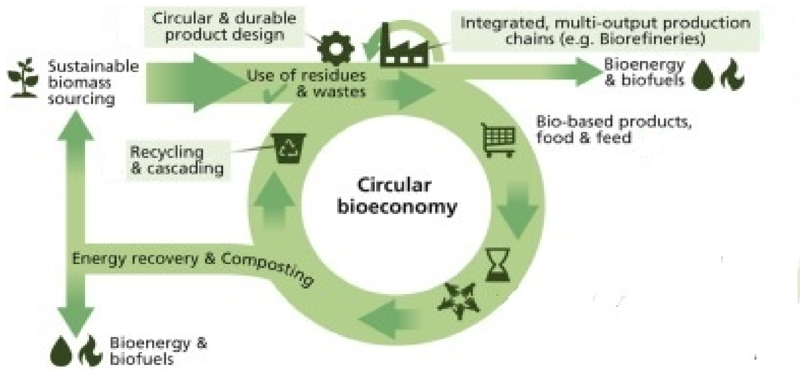

Figure 1: CBE concept and integrated biorefenery [58]

In line with these findings the EU has established several goals and policies aimed to foster the growth of the CBE and the development of biorefineries, thereby recognizing the bio-based products sector as a key enabling technology sector. The strategies include measures to develop markets and enhance competitiveness in bio-based sectors, such as increasing primary production, converting waste into valuable products through bio-refineries, and implementing mechanisms for improved production and resource efficiency [18].

1.2 Bio-based value chains for chemical synthesis

Building upon the EU's established goals and policies to foster the growth of the CBE and biorefineries, which recognize the bio-based products sector as a key enabling technology, it is important to examine the concept of bio-based value chains. Bio-based value chains are defined as the sequence of processes from biomass production to bio-product along with its opportunities for value generation, including economic, social and ecological values. An integrated bio-based value chain optimizes the interaction of these processes and the material flows involved, with the objective of optimizing the overall performance in economic, ecological and social terms [40]. One important value-chain in the circular bioeconomy is the biomass-to-x route, which involves converting biomass feed-stocks such as wood, agricultural residues, and other organic materials into a range of value-added products such as biofuels, biochemicals, and biomaterials [3]. This conversion process is facilitated in bio-refineries, which can be classified on the basis of the conversion route, namely thermo-chemical or biochemical biomass refining. Gasification, widely recognized as the most efficient route, is a thermochemical refining process that takes place at high temperatures, typically ranging from 500 to 1400 °C [1]. It involves the conversion of biomass in the presence of a gasifying agent, such as air, oxygen, or steam. This process transforms biomass into a valuable gaseous product known as syngas. Syngas is predominantly composed of hydrogen (H2) and carbon monoxide (CO), alongside other gases like carbon dioxide (CO2), water (H2O), methane (CH4), and nitrogen (N2) [46]. Syngas already serves as a crucial intermediate in the chemical industry and finds applications in the selective synthesis of a wide variety chemicals and fuels, such as Fischer-Tropsch liquids, methanol, ammonia, hydrogen, and carbon monoxide (see figure 2) [1]. Additionally, the gasification process yields a solid byproduct called char, which comprises the unconverted organic fraction and ash. The composition of both the syngas and char is influenced by the specific biomass feedstock used and the operational conditions employed during the gasification process [46].

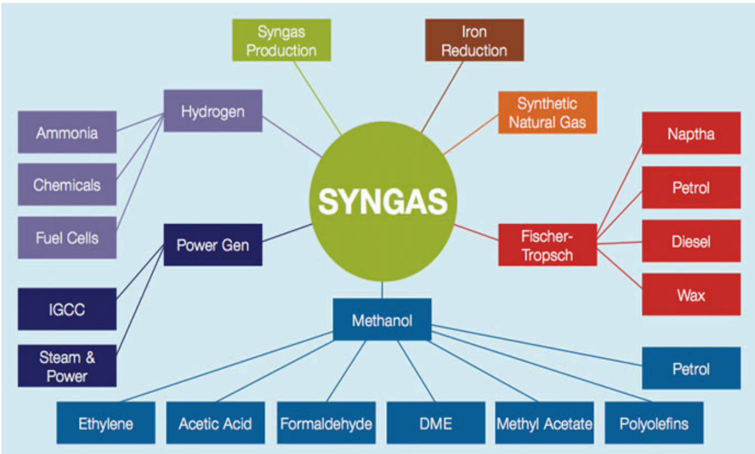

Figure 2: Versatility of syngas

Due to its versatility and compatibility with existing chemical conversion routes, the production of bio-based syngas is believed to hold great potential for the development of bio-refineries. Researchers are therefore optimistic that this development of thermo-chemical bio-refineries will not only strengthen the economy but also have a positive impact on the environment, while creating job opportunities at the local, national, and international levels [37]. Moreover according to Awasthi et al. and Akbarian et al. bio-refineries are integral to supporting a knowledge-driven and environmentally robust low-carbon circular bio-economy by manufacturing high-value materials from biomass. Therefore around the globe, there is a growing interest in the development of these sustainable biorefinery approaches, however the yields and profits of these technologies are still unable to compete with fossil fuel based technologies [57]. The uncompetitive yields and profits are mainly caused by technical challenges of the gasification technology such as tar formation, product impurities, and soot which have made industrial development difficult. Moreover biorefeneries also face major commercial challenges such as financing, market maturity, and availability of the sustainable feedstock [16].

1.2.1 Torrefaction

Apart from the technological and economical challenges that biorefineries face, setting up such bio-based value chains face constraints with the handling and use of biomass as a feedstock. The major constraints that the direct use of raw biomass faces are high moisture and oxygen content, low energy density, hydrophilic nature, and highly variable composition and properties [13][15]. These constraints can lead to operational concerns during the thermal conversion of biomass in biorefenery practises, such as high-energy demand for grinding and pelletisation, poor ignition properties, low combustion temperature, inefficient combustion, and fume and flue gas production. Furthermore, the hydrophilic properties of the biomass can cause problems related to the storage and energy density of the biomass, causing the biomass to be unstable and likely to deteriorate biologically [13][15]. The complexity and heterogeneity of raw biomass therefore restrict the conversion efficiency and costs [52]. Moreover raw biomass being high-volume and low-density, has high transport costs and cannot be efficiently transported over long distances. The utilization of agricultural residues as fuel is therefore constrained by geographics and seasonal production and lower energy content per ton compared to fossil fuels [3]. Considering these challenges, biomass needs to be pretreated to improve its characteristics and thereby improve efficient utilisation during thermal conversion processes. Moisture content reduction is a crucial aspect of this pretreatment, as it significantly improves product quality, enhances energy efficiency, improves transportability, and reduces gaseous emissions from thermo-chemical energy conversion processes [2].
Torrefaction technology has emerged as a promising solution for addressing the aforementioned drawbacks of raw biomass. It involves a low-temperature process, resembling pyrolysis, conducted at heating rates below 350°C (see Figure 3). The primary product of torrefaction is a solid material known as torrified biomass, also referred to as biocoal or biochar. The improved properties of torrified biomass can be attributed to the removal of oxygen from raw biomass in the form of volatile gaseous components (CO2, H2, CH4, and CO) and liquid compounds (such as acids, phenols, furans, and ketones) [15].

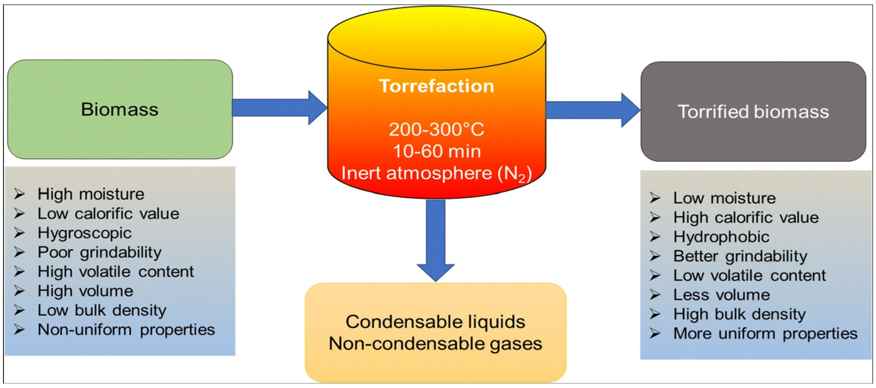

Figure 3: Torrefaction process [54]

Torrefaction offers several benefits in the biomass conversion process. Firstly, it enhances biomass densification, leading to improved pellet quality and better performance in combustion and gasification processes. Additionally, torrefaction reduces the moisture content of biomass, increasing its flammability and hydrophobicity. This results in enhanced storability with reduced risk of biological deterioration [16] [13]. The reduced moisture content also facilitates bulk transport, handling, and conversion of torrified biomass, thereby lowering transportation costs [54]. Moreover, torrefaction positively impacts subsequent thermo-chemical conversion technologies in the biomass-to-x value chain, including pyrolysis, gasification, combustion, and co-firing. Since, by weakening the inherent structural chemistry of biomass, torrefaction makes it more susceptible to thermal degradation during these processes [54].
Therefore it is clear that torrefaction holds great promise as a pre-treatment step in the biomass-to-X value chain for biorefinery applications. However, it is still an emerging technology with a limited number of commercially available reactors [16]. While research on biomass torrefaction has advanced, its widespread commercial implementation is yet to be realized, and uncertainties surrounding its economic feasibility persist. Further advancements are needed in critical areas such as kinetics, reactor design, fuel adaptability, process management, heat utilization, and scaling up. Additionally, considerations related to raw material availability, transportation logistics, environmental impact, financial performance, plant size, and site selection must be carefully addressed to facilitate broader adoption of torrefaction in the industry [61].

1.3 Problem description

While the potential of developing the bio-based value chain through gasification and torrefaction for decarbonizing syngas production and chemical synthesis is evident, the current cost of these conversion processes presents a challenge in competing with established fossil-fuel technologies [16]. As a result, the production of sustainable olefins and chemicals from biomass through these processes is not yet economically competitive compared to current market prices, and gasification processes still heavily rely on fossil resources. This limited adoption of the technologies and biomass utilization in the industry is reflected in the uptake shown in Figure 4 underneath [1].

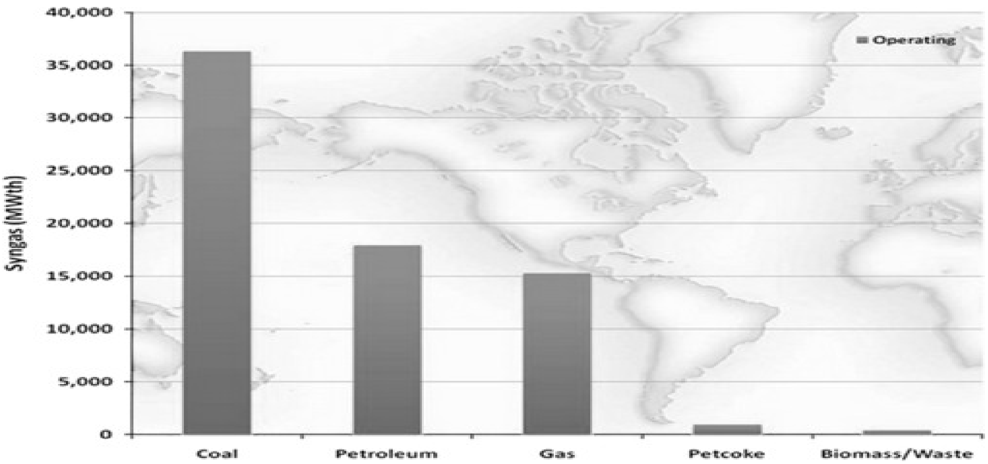

Figure 4: Overview of worldwide feedstock usage for syngas production [1]

Therefore in order to drive the development of these sustainable bio-based value chains it is crucial for research to aim at reducing the overall cost of developing bio-based value chains. While enhancing the technical performance of biomass processes can greatly improve their commercial viability, it is crucial to consider Berg et al.'s emphasis that the establishment of these value chains should not depend solely on technological advancements. The lack of information concerning system integration and practical applications of biomass in the chemical industry also poses a significant challenge that must be addressed [6]. Therefore, a comprehensive approach is needed, focusing not only on technological improvements but also on gaining a deeper understanding of system integration and practical implementations, in order to foster the successful development of bio-based value chains. Hence, researchers such as Stegmann et al. and Akbarian et al. therefore emphasize the necessity of adopting a multi-dimensional approach involving governments, stakeholders, and the facilitation of cooperation along and across supply chains to effectively address these challenges and drive the sustainable development of biorefineries [58] [2]. However, academic research concerning the advancement of the biomass to chemicals value chain through gasification predominantly concentrates on recognizing a diverse array of barriers and drivers for their progress and that of the CBE. The focus of these researches primarily centers around exploring solutions that are subject to disagreement among the actors involved in the value chain, highlighting the contrasting perspectives and viewpoints of these actors (Lewandowski; Stegmann et al. ; Akbarian et al. ; Kardung et al.). In addition, there is a noticeable research gap regarding the integration of torrefaction technology into the biomass-to-syngas value chain within the context of biorefineries. Existing studies primarily concentrate on aspects such as mass and energy balance, kinetics, and energy-related applications of the technology, such as the researches of Cahyanti et al., Chen et al., Bach & Skreiberg. However, there is a absence of research that explores the comprehensive system integration of torrefaction in the biomass-to-X value chain, encompassing the perspectives of governments, stakeholders, and the promotion of collaboration along and across the value chain. Therefore, there is a clear need for further research which investigates the development and system integration of torrefaction within the biomass-to-biochemicals value chain by actively involving stakeholders from across the product chain. Additionally there is a need for research which adopts a multi-dimensional approach involving governments, stakeholders, and the facilitation of cooperation along and across the value chain to effectively address the challenges which impede the sustainable development of biorefineries.

1.4 Research Scope & objective

As can be derived from the preceding sections, the chemical industry is confronted with a significant challenge in terms of its sustainability. To enhance the industry's sustainability and reduce carbon emissions, the development of the biomass-to-X value chain, specifically for sustainable syngas and chemical production, is an important pathway. However, despite the potential of such a bio-based value chain, the current high cost of the conversion processes, biomass gasification and torrefaction, hinder their competitiveness against fossil-fuel technologies. Moreover, the lack of information on system integration in the chemical industry further restricts the adoption of these technologies.
Therefore this research aims to address these challenges by investigating the strategies that can be implemented to effectively drive the development of this biomass-to-syngas value chain. The research involves active engagement with stakeholders and experts from the industry to gain valuable insights into the main barriers and collaborative solutions for the value chain's development. Additionally, the research will focus on stakeholders' perspectives on the role and implementation of torrefaction technology within this value chain. By considering these aspects, the study seeks to provide comprehensive insights for the development of the biomass-to-syngas value chain and the effective integration of torrefaction technology in it.
Based on the previous sections the value chain can roughly be divided into four sequential steps: biomass collection and trade, torrefaction for biochar synthesis, gasification of biochar for syngas production, and the synthesis of various fuels and chemicals. Considering that the synthesis of chemicals from syngas already relies on established technologies like gas-shift reactors and the Fischer-Tropsch process [1], it was decided not to include this step in the study in order to conduct a more detailed analysis of the value chain. Therefore, the research specifically investigates the biomass-to-syngas value chain rather than the broader biomass-to-X value chain. Moreover the thesis studies a specific case in which the Dutch chemical industry has been chosen as the case study, offering the opportunity to examine the intricacies, challenges, and opportunities within the value chain system. By focusing on the biomass-to-syngas value chain in the Netherlands, the study aims to capture the contextual factors specific to the Dutch chemical industry, allowing for the facilitation of in-person stakeholder interactions and providing a delineation of the value chain system. It is important to note that this delineation to the specific case of the Dutch chemical industry might constrain the generalizability of this study, however by recognizing and addressing these limitations, the thesis aims to ensure the validity and reliability of its findings.
In terms of the research methodology, a step-wise approach will be employed, combining qualitative and quantitative approaches. Data will be collected through an analysis of relevant industry reports and literature, conducting semi-structured interviews, administering a questionnaire, and organizing an expert panel discussion. This step-wise approach aims to gain a holistic understanding of the current state and barriers hindering the widespread adoption of the value chain, facilitating the iterative formation of theory based on insights derived from literature and stakeholders' input. Grounded theory will be employed to code and categorize the collected data, while thematic analysis will be utilized to extract meaningful insights and identify key strategies for advancing the biomass-to-syngas value chain within the Dutch chemical industry. Additionally, content analysis will provide quantitative insights into the most significant deficiencies in the value chain's building blocks.

1.4.1 Research objective

From the previously described problem description a research objective can be derived which focuses on two knowledge gaps in scientific literature. Firstly, there is a clear need for research which actively engages with stakeholders from different stages across the product chain to investigate and address the challenges associated with the development of the biomass-to-biochemicals value chain. Central in this research is the development of comprehensive solutions within the biomass-to-biochemicals value chain through active stakeholder involvement. Hence this research aims to explore and propose solution strategies that can facilitate collaboration, innovation, and sustainable development of the Dutch biomass-to-syngas value chain.
Another knowledge gap in scientific literature is the lack of research that explores the system integration of torrefaction technology in the biomass-to-syngas value chain within the context of biorefineries. Where existing studies mainly focus on aspects such as mass and energy balance, kinetics, and energy-related applications of torrefaction. This study aims investigate the development and system integration of torrefaction within the biomass-to-syngas value chain by actively involving stakeholders from across the product chain and gaining insight on the industry perspective on the integration of torrefaction in the value chain.

1.5 Research questions

Since the overall aim of this thesis is to address the identified knowledge gaps regarding the system integration of torrefaction technology in the biomass-to-syngas value chain, as well as investigate solution strategies which can facilitate collaboration, innovation, and sustainable development of the Dutch biomass-to-syngas value chain. The following research objectives have been drafted to support the overall goal of this thesis:

- Identify and gain insight on the barriers and solutions of the Dutch biomass to syngas value chain from both literature and stakeholder input.
- Prioritize barriers and solutions based on stakeholder input.
- Propose and evaluate solution strategies for enhancing collaboration, innovation, and sustainable development in the Dutch biomass-to-syngas value chain.
- Obtain and analyse stakeholder perspectives on the integration of torrefaction technology into the value chain.
- Validate and refine research findings on solution proposals through expert reflection

By fulfilling these objectives this research can provide valuable insights into the feasibility of scaling up the biomass to syngas process and its potential impact on increasing sustainable practises in the Dutch chemical industry. These objectives can be fulfilled by obtaining the answer to the following main research question: *What strategies can be implemented to effectively drive the development of the biomass-to-syngas value chain for bio-based chemical production in the Netherlands, taking into account industry stakeholders' perspectives, key barriers, and mutually derived solutions?*
To address this the main research question, the following seven sub-questions have been formulated, each concentrating on a specific aspect of the research, these sub-questions are as follows:

- What are the main building blocks of the value chain's innovation system that influence and hinder the development of the Dutch biomass-to-syngas value chain?
- What are the barriers identified by stakeholders in the Dutch biomass-to-syngas value chain, and what solutions do they propose to address these barriers?
- How do stakeholders prioritize the identified barriers to development of the Dutch biomass-to-syngas value chain?
- What are stakeholders' perspectives on the implementation and role of torrefaction technology in the value chain?
- What potential solutions can be derived from stakeholders to address the prioritized barriers in the biomass-to-syngas value chain?
- How do experts assess the barriers and solutions, derived from stakeholders' perspectives, for the development of the biomass-to-syngas value chain?
- How do experts evaluate the implementation and role of torrefaction technology in the value chain?

Addressing the first two questions provides an overview of the key building blocks and their impact on innovation in the Dutch biomass-to-syngas value chain. These questions offer insights into factors influencing innovation, collaboration, and progress. Additionally, the second research question identifies challenges perceived by stakeholders, providing context to failures in the innovation system and understanding value chain obstacles. Moreover, stakeholders' proposed solutions and recommendations are gathered, offering potential strategies to drive value chain's development.
The third question prioritizes barriers to the value chain's development based on stakeholder input. It thereby identifies critical obstacles according to stakeholders, narrowing the focus for deriving solution strategies to these most pressing barriers.
The fourth question gathers stakeholders' insights on the implementation and role of torrefaction technology in the value chain. By analysing stakeholders' perceptions, opinions, and expectations regarding the integration of torrefaction technology, a holistic understanding of the technology's implications, benefits, challenges, and contributions to the development of the value chain can be created.
The fifth and sixth sub-questions identify stakeholder solutions to overcome prioritized barriers and gather

expert opinions on these identified barriers and proposed solutions. By considering these solution proposals, the research aims to generate solution strategies and critically assess challenges and potential strategies. The subsequent expert reflection validates the relevance, feasibility, and effectiveness of identified barriers and solutions.
Lastly, the seventh sub-question seeks to gather expert opinions and evaluations on the implementation and role of torrefaction technology within the biomass-to-syngas value chain. Thereby the research aims to gain a broader and more informed understanding of the implications, advantages, limitations, and potential outcomes associated with the integration of torrefaction technology.
Overall, by combining the insights gained from addressing these sub-questions, the main research question can be effectively answered. Thereby leading to the development of solution strategies aimed at driving the advancement of the biomass-to-syngas value chain for bio-based chemical production in the Netherlands.

1.6 Relevance

1.6.1 Relevance to the study program

This research fits well with the Management Of Technology program due to several overarching themes. Firstly, the thesis focuses on the development of the biomass-to-syngas value chain, which involves the application of technology in the production of bio-based chemicals. It addresses the challenges and barriers related to technology and innovation processes within this context. Moreover, the research recognizes technology as a corporate resource by exploring how firms can use technology to drive the development of the biomass-to-syngas value chain. For example, the thesis investigates the impact of incorporating torrefaction technology and formulates strategies to overcome barriers, improve outcomes, and enhance corporate productivity and competitiveness.
Additionally, the research in this thesis is based on multiple scientific methods and techniques, including an exploratory literature review, semi-structured interviews, a questionnaire, and a webinar panel discussion. These methods align with need for a scientific approach emphasized in the MOT curriculum, demonstrating the researchers ability to use research methods in order to analyze and address the problem at hand.
Lastly, the research covers various aspects relevant to the MOT program, such as technology and strategy, research and product development management, innovation processes, and entrepreneurship. It explores stakeholder perspectives, identifies barriers, and formulates strategies to effectively manage technology and innovation in the context of the biomass-to-syngas value chain.
In conclusion, the thesis fits well within the Management of Technology program as it conducts a scientific study in a technological context, understands the importance of technology as a resource for businesses, and applies scientific methods to analyze and solve problems. This research therefore aligns with the program's focus on using technology for strategic management, innovation, and achieving favorable organizational outcomes.

1.7 Thesis outline

This thesis comprises nine chapters. Following this introduction, Chapter 2 presents the research methodology employed, providing context on the case of the chemical industry in the Netherlands. Chapter 3 summarizes the relevant actors, stakeholders, and experts involved in the research. Chapters 4 to 7 delve into the research findings, following the step-wise approach. Chapter 4 examines the identified barriers and analyzes the failures in the value chain's innovation system. Chapter 5 focuses on the perspectives of industry stakeholders regarding the value chain's development and the integration of torrefaction technology. Chapter 6 discusses the prioritization of barriers, while Chapter 7 explores the development of solutions and the outcomes of the expert reflection session. Finally, Chapters 8 and 9 provide a discussion and conclusion based on the research findings respectively.

2 Theoretical framework

As outlined in section 1.3, the existing body of scientific knowledge lacks a comprehensive understanding and exploration of the diverse perspectives and viewpoints of actors involved in the biomass-to-chemicals value chain, as well as the integration of torrefaction technology. Where current studies have predominantly concentrated on identifying barriers and drivers based on the technical aspects of these technologies, a significant research gap exists in addressing the variations in opinions and collaboration among stakeholders within the value chain concerning the development of these technologies. Furthermore, there is a clear need to investigate the comprehensive system integration of torrefaction technology in the biomass-to-syngas value chain, taking into account government perspectives, stakeholder engagement, and the promotion of collaboration.
The purpose of this chapter is to develop a theoretical framework that effectively addresses the research gap and serves as a solid foundation for subsequent research steps and methodology. The framework aims to adopt a multi-dimensional approach, capturing diverse stakeholder perspectives, promoting collaboration, and exploring comprehensive system integration.
To achieve this goal, the chapter presents a theoretical framework that combines two prominent approaches, namely the Solution-focused Sustainability Assessment (SfSA) and the Technological Innovation System (TIS) approach. By integrating these two frameworks, the research can achieve a more comprehensive understanding of the barriers and dynamics influencing the development of the value chain. Moreover this innovative integration of these two scientific frameworks allows for a holistic exploration of the problem, fostering inclusivity and collaboration among various stakeholders, and leading to the identification of innovative solutions aligned with the sustainable development of the value chain.

2.1 Solution-focused Sustainability Assessment

The Solution-focused Sustainability Assessment (SfSA) framework, introduced by Zijp et al., offers a theoretical foundation for addressing the identified research gap in the context of sustainability transitions, such as the development of the biomass-to-syngas value chain. This innovative approach offers a systematic and step-wise qualitative methodology, enhanced by van Bruggen et al. with a 'chain approach,' (see Figure 5). This approach aims to engage stakeholders from various points along the value chain through a transformative process in order to foster collaboration, innovation, and the exploration of multiple viewpoints in a developing and innovative value chain [62]. The SfSA framework follows six successive and iterative steps which promote flexibility and enable comprehensive problem-solving through stakeholder involvement. Supported by a mixed methods qualitative methodology, the framework facilitates the identification of innovative solutions, considering the entire value chain and stakeholders' diverse perspectives [68]. Ultimately, the SfSA framework facilitates a holistic exploration of the problem, leading to innovative solutions that align with stakeholder needs and aspirations [62].

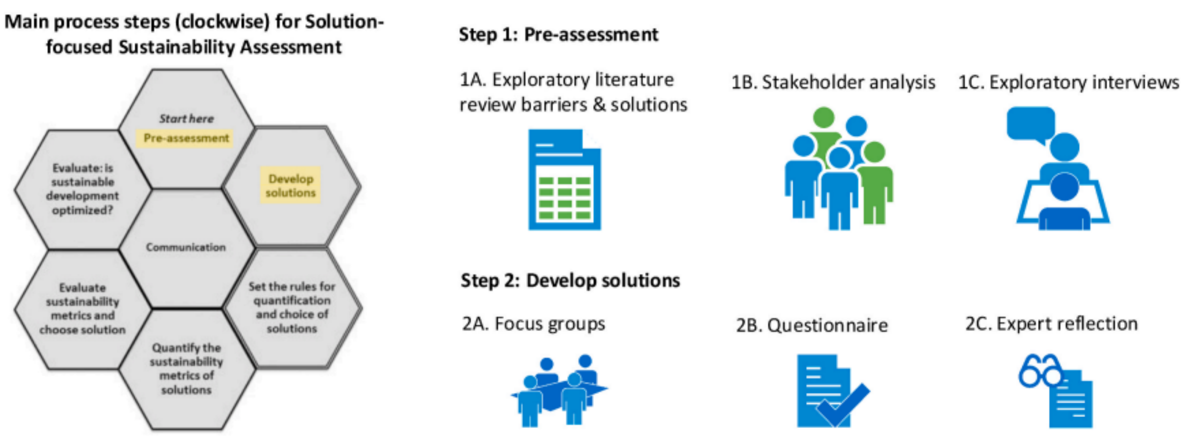

Figure 5: Steps of solution-focused sustainability assessment, including the chain approach in step 1 and 2 of the framework [62][68]

The SfSA framework arises from key theoretical frameworks such as risk assessment, risk governance, and sustainability assessment. However, although these frameworks have long been employed in environmental assessment and management practices, they generally tend to focus on the identification of the type and magnitude of a (risk) problem rather than on exploring low-risk or high-sustainability solutions [68]. The SfSA framework therefore merges these frameworks by incorporating a solution-focused perspective, allowing for a shift in focus from solely identifying problems to also exploring potential solutions. Therefore the SfSA approach encourages the exploration of diverse solutions upfront, without predetermined limits, enabling innovative approaches for complex and wicked problems. By integrating these frameworks, the SfSA framework provides a comprehensive approach that considers both the problem and solution space, facilitating the identification of alternative solutions when traditional approaches, e.g., those focusing on single-metric risk assessments, fall short [68].
Additionally, the SfSA framework incorporates several key elements of sustainability assessment frameworks which include the consideration of varying societal views on the problem, the definition of sustainability, and the decision context. The approach therefore emphasizes the transparent and participative translation of these views into methodological choices. This participative translation refers to a process in which stakeholders are invited to discuss the design of the sustainability assessment [62]. For example, considering the question which themes or barriers are most important. Therefore, effective communication plays a central role within and across assessment steps and when interacting with stakeholder groups. Furthermore, the SfSA framework emphasizes iterative learning and evaluation, incorporating adaptive management approaches to address wicked problems. Stakeholder participation is therefore integral to evaluating the success of implemented solutions, as different views on the problem influence the assessment. These interactions and communication processes are essential components of the SfSA cycle, ensuring comprehensive engagement and collaboration throughout the assessment [68].
Overall, SfSA framework provides a qualitative, solution-focused approach in sustainability transitions, serving as a theoretical foundation for exploring alternative solutions by engaging stakeholders across a value chain [68]. The framework thereby represents a valuable tool for researchers, policymakers, and industry practitioners, by promoting sustainable practices and facilitating the transition to circular value chains. Additionally, the chain approach, introduced by van Bruggen et al., further enhances the assessment of circular solutions and policy pathways by capturing diverse stakeholder perspectives [62]. The SfSA framework therefore offers a multi-dimensional approach involving stakeholders from the entire value chain to derive mutually agreed solutions for overcoming barriers to the value chain's sustainable development. Therefore, the SfSA framework effectively addresses the identified research gap and provides valuable insights into the development of the biomass-to-syngas value chain.. Moreover, by employing the framework's chain approach, a deeper understanding of diverse stakeholder perspectives on torrefaction technology integration can be gained, further promoting the sustainable development of this technology within the value chain [62].

2.2 Enhancing the SfSA Framework by integrating the TIS-building block Approach

However, while the SfSA framework offers a valuable approach for studying stakeholder perspectives and deriving solutions for value chain development and sustainability, it has a limitation concerning the system perspective for studying technology development. The framework primarily concentrates on stakeholder involvement without explicitly considering the broader systemic context in which the technology operates. Although stakeholder involvement is crucial, understanding the interdependencies, feedback loops, and systemic dynamics within the value chain is essential for a comprehensive analysis of technology development [8]. Additionally, the SfSA framework's approach to barrier analysis and categorization may be underdeveloped in the context of studying the development of a value chain. The framework lacks a systematic and structured process for identifying and categorizing barriers that are specific to the dynamics of the value chain and the integration of the technology. This limitation can hinder the effectiveness of the analysis and impede the identification of critical barriers that significantly impact the development of the value chain.
Therefore to address this shortcoming of the SfSA framework, this study proposes a theoretical framework in which the barrier identification, categorization, and analysis process of the SfSA method (step 1) is merged with the Technological Innovation System (TIS) approach as proposed by Ortt & Kamp. By integrating the TIS framework, which emphasizes a system-level perspective and a structured approach to barrier analysis, the research can overcome the limitations of the SfSA framework and provide a more comprehensive understanding of the barriers and dynamics influencing the development of the value chain

[48].
A Technological Innovation System (TIS) represents a socio-technical system centered around a specific technological innovation. It can be defined as a dynamic network of agents interacting in a particular economic or industrial area, operating within a specific institutional infrastructure, and engaged in the generation, diffusion, and utilization of a technology [14]. The TIS framework thereby focuses on understanding how the innovation system around a particular technology operates and can be applied to both mature technological fields and the emergence and diffusion of new and radical innovations [8]. Many studies utilizing the TIS framework have centered on the emergence of clean-tech sectors, making it a crucial component of sustainability transitions research. In the field of such sustainability transition studies, TIS contributes with an analytical framework for understanding the complex nature of the emergence and growth of new industries and the analysis of obstacles that affect the development of new industries, referred to as blocking mechanisms, system weaknesses, or systemic problems. Moreover, the framework aids in the subsequent formulation of intervention and policy strategies, leading to concepts such as systemic instruments and policy mixes [7]. In this regard, the TIS framework aligns well with the Solution-focused Sustainability Assessment (SfSA) approach. Together, these frameworks can therefore form a powerful combination, providing a systematic methodology for studying the development of value chains within sustainability transitions.
Specifically, integrating the TIS-building block framework as proposed by Ortt & Kamp into the SfSA approach can be effectively employed to analyze and categorize barriers to the development of the biomass-to-syngas value chain during the initial step of barrier identification and categorization. This framework is based on a combination of methodologies stemming from various research fields, including strategic niche management, technological innovation systems, and transitions [48]. The framework proposes seven building blocks of a TIS formulated such that each of them, once missing, incomplete or incompatible with each other and the innovation, would form a barrier to large-scale diffusion of the technology and value chain (see table 1 below). Therefore a complete and compatible set of these building blocks is required for large-scale diffusion of the technologies and value chain [48]. By categorizing barriers identified through stakeholder interaction in step 1 of the SfSA method according to these building blocks, valuable insights into the dynamics of the value chain system can be gained. Thereby this process allows for a deeper understanding of how the barriers align with specific building blocks and their impact on the overall diffusion of torrefaction technology and biomass-to-syngas value chain itself.

TIS building blocks	
Building block	**Description**
Product performance and quality	Does the new product have sufficiently good performance or quality now, or in the near future, when compared to competing products?
Product price	The product price involves both financial and non-financial cost, i.e. selling and depreciating investments in previous products, switching costs and transaction cost. The new product is required to have a reasonable price absolutely or relatively to other competitive technologies.
Production system	Is the production system capable of delivering high quality products in large quantities? or will growing experience with the production system increase the product's quality and decrease production costs?
Complementary products and services	Are there complementary products and services available that support the development, production, distribution, adoption, use, repair, maintenance and disposal of the innovation?
Network formation and coordination	Multiple types of actors are vital for large-scale diffusion of an innovation. Actors can refer to suppliers of parts, actors assembling or producing the product, distributors, and actors providing complementary products and services. In addition, the coordination between these actors is also important and can consist of not only actual collaboration but also a shared vision regarding the technology.
Customers	Customer segment needs to be identified early on. Customers should be aware of the technology, see its benefits compared to other products and have the knowledge, means and willingness to acquire and use it.
Innovation specific institutions	These institutions refer to formal and informal rules such as government policies, laws, standards and regulations

Table 1: Building blocks to TIS development and large-scale technology diffusion [48][8][31]

However, although assigning these building blocks to the identified barriers gives an insight into the nature of the barriers, this will not always provide enough information to assess the type solution strategy needed to overcome the barrier [48]. Understanding the cause of a barrier is therefore essential as different causes may necessitate different solution strategies. Consequently, Ortt & Kamp identified seven 'influential conditions' (Table 2) by analyzing scientific literature on barriers to new technological innovations from both the company and governmental perspectives. Therefore, by connecting the barriers to these influential conditions insight can be created into the cause of the barriers, thereby allowing for the development of fitting solution strategies during the solution development phase (step 2) of the SfSA approach.

Influencing factors	
Factor	**Description**
Knowledge and and awareness of technology	Both fundamental and applied technological knowledge is required for TIS formation.
Knowledge and awareness of application and market	Refers to the knowledge on how, and in which applications, the innovation can be used and knowledge of the market structure and the relevant actors involved. This knowledge can be developed through market analysis, experimentation, learning by doing, learning by using or learning by interacting with relevant actors in the socio-technical system. All actors in the TIS can suffer from a lack of knowledge and awareness of the application.
Natural, human and financial resources	Natural resources to create products, production systems and complementary products can be acquired by each actor separately or by associations of organizations. Secondly, human resources with appropriate knowledge and competences, need to be mobilized. The appropriate knowledge and competences may be acquired via education programs or courses or in practice, via learning by doing. Thirdly, financial resources are needed for development and application of the innovation, the production system and complementary products and services. Financial resources can come from different types of actors, such as supplying companies, investors, governmental institutions, or customers.
Competition	Especially during TIS formation, innovations based on old technologies compete with those based on new technologies. Moreover different product versions can compete which can create uncertainty in the TIS formation. Competition can detimine the relative price and performance of the innovation.
Macro-economic and strategic aspects	The macro-economic situation involves conditions like the market structure and the contemporary way of doing business, and these conditions are often reflected in strategic policies of countries regarding important industries. The combination of these conditions can influence the formation of TIS building blocks
Socio-cultural aspects	Socio-cultural aspects refer to the norms and values held by potential customers and other important stakeholders in the socio-technical system. These aspects may be more informal than the laws, rules, regulations and policies mentioned as institutions but they can have a large impact on the formation of these institutions and on the behaviour of the actors in the TIS.
Accidents and events	Accidents can refer to accidents within the TIS, such as an accident in production or an accident by a product that fails. Accidents can also refer to accidents outside the TIS, such as wars or natural disasters. Both can have a large impact on several building blocks in a TIS. Some accidents may also stimulate TIS formation for radically new technological innovations.

Table 2: Influencing factors to barriers of large-scale technology diffusion [48] [31] [8]

2.3 Conclusion

In this chapter, a theoretical framework was developed which combines the Solution-focused Sustainability Assessment (SfSA) and Technological Innovation System (TIS) frameworks, resulting in a comprehensive and multi-dimensional approach. This framework captures diverse stakeholder perspectives, fosters collaboration and engagement, and provides a holistic understanding of the value chain dynamics. The framework thereby effectively addresses the research gap in providing solid foundation for understanding stakeholder perspectives and collaboration within the biomass-to-syngas value chain.

While the SfSA framework employs a systematic and qualitative methodology, encouraging stakeholder involvement for innovative and sustainable solutions it has limitations in terms of incorporating a technology development perspective and structured barrier analysis. By integrating the TIS-building block framework, the SfSA approach was enhanced, enabling a deeper analysis and categorization of barriers, intervention strategies, and system dynamics within the value chain. Additionally, this study extends the literature by applying the novel SfSA theory to a third case and improving it through the incorporation of the TIS approach. The combined theoretical framework thereby offers a robust methodology for analyzing value chain dynamics, identifying barriers, and formulating effective solution strategies. In the subsequent chapter, the research methodology will be derived from this framework to study the biomass-to-syngas value chain in the Netherlands, with a specific focus on torrefaction technology integration.

3 Mixed qualitative methods

This section describes the mixed qualitative research steps together with the characteristics of the case study. The described methodologies will be used to obtain valuable insights into the structure, stakeholders and barriers in the Dutch biomass-to-x value chain. Ultimately the insights obtained using the proposed research method will answer the posed research questions.

3.1 Case study

In order to obtain an in-depth understanding of the biomass-to-x value chain and sustainability within this system it necessary to select a complex case which introduces the use of innovative thermo-chemical biomass technologies for the production of syngas. Therefore the biomass-to-x value chain in the Netherlands was selected to serve as a case-study, since this allows for the facilitation of in-person stakeholder interactions and a delineation of the value chain. Moreover the Netherlands holds great potential for the implementation of biomass-to-x. The country has a relatively high final energy consumption due to important role of industries in the country, which represents a share of 45% of final consumption of energy carriers in the Netherlands, of which an important part goes to non-energy uses, e.g. in chemical industries [9]. Moreover the country has stated its ambitions for increased use of sustainable biomass in various sectors. In the longer term, the Dutch government aims to use sustainable biomass for high-value applications in economic sectors where there are few alternatives, such as raw materials in the industry and fuel for heavy vehicles and aviation and shipping. By 2030, this should be taken into account in the extent to which applications are stimulated or discouraged [38]. Additionally, the Dutch Climate Agreement includes the ambition of producing 2 billion cubic meters (BCM) of green gas by 2030 as part of the goal to transition towards sustainable heating and achieve CO2 reduction. Therefore, the country's new biomass sustainability approach puts a strong focus on biorefineries to capture the value of bioresources in an efficient way, thereby stimulating the development of the biomass-to-syngas value chain [9].This further underscores the importance of studying the use of biomass as a sustainable transition resource in the Netherlands and the potential role of green (syn)gas in achieving the country's sustainability targets [34].

3.1.1 Dutch chemical industry & current status

The chemical industry in the Netherlands ranks fourth in terms of revenue in Europe and tenth globally. This essential basic industry for the Dutch economy employs 45,000 workers and generates € 71 billion in annual revenue, accounting for nearly 19 percent of the country's exports. Remarkably, despite comprising only 0.2 percent of the world's population, the Netherlands accounts for approximately 2 percent of the global chemical industry. This can be attributed to several factors that have been instrumental in establishing the country's current position. These factors include the favorable geographical location of the Netherlands, boasting seaports and efficient connections to the European hinterland. Additionally, the country benefits from a stable and reliable government, a highly educated workforce, and internationally renowned knowledge institutions [65].

Figure 6: Overview of Dutch chemical industry [65]

The chemical industry is often referred to as the "industry of industries" due to its pivotal role in supplying raw materials for 97 percent of all industrial production [60]. As a result, the chemical industry in the Netherlands significantly contributes to the overall emissions and environmental impact associated with industrial activities, accounting for 41 percent of the total greenhouse gas emissions within the Dutch industrial sector [28].
In this regard the Royal Assocation of the Dutch Chemical Industry (VNCI) has expressed the opportunity

and need to increase the sustainability of the sector by focusing on the use of bio-based raw materials, recyclable waste and the reuse of CO_2, to replace fossil raw materials with sustainable alternatives. Hence, the industry has formulated a strategy to transition towards a sustainable chemical industry. This entails not only reducing the emissions originating from production processes but also addressing the carbon impact throughout the entire life cycle of the products. As most chemical value chains currently follow linear arrangements and rely on fossil-based raw materials, the industry is therefore actively pursuing circularity in both its products and production processes. In order to achieve this circularity the industry states three technical approaches are needed [64]:

- Mechanical and chemical recycling to close the loop and prevent incineration at the end of the product life cycle.
- The use of bio-based feedstocks to offer a solution for creating products without relying on fossil carbon, thus avoiding the formation of fossil CO_2 during the product's life cycle.
- Carbon capture and CO_2 reuse in order to reintegrate CO_2 back into the production chain, preventing emissions at the end of the product's use phase.

In conclusion, it is clear that the chemical industry holds a significant role in the national economy. The country's commitment to sustainability and the utilization of sustainable biomass for high-value applications in sectors with limited alternatives, combined with the strategic emphasis of the Dutch chemical sector on bio-based feedstocks and chemical recycling, provides strong justifications for studying the development of the biomass-to-syngas value chain in the Netherlands. Conducting a case study in this area can therefore lead to valuable insights into the opportunities and challenges associated with the development of the biomass-to-syngas value chain for the production of bio-chemicals.

3.1.1.1 exemplary case

This research employs a case study approach to investigate the process and actors within the biomass-to-syngas value chain for the chemical sector, focusing on the context of the Netherlands. The research was conducted during a graduation internship at Uniper, offering valuable insights into a tangible biomass-to-syngas project known as BrigH2. The primary objective of BrigH2 is to demonstrate the feasibility of a biorefinery through the gasification of torrified raw biomass, and sustainably produce the valuable by-products of hydrogen, bioCO_2, and bioChar on an industrial scale. Initially, a 50 MW gasification unit will be implemented, with a subsequent plan to scale up to 400 MW. The BrigH2 demonstration plant will be strategically situated on the Brightlands Chemelot Campus, serving the industrial users within the Chemelot site.
Furthermore, the research aims to study the entire value chain associated with the project, spanning from biomass acquisition and torrefaction to syngas production and its subsequent distribution within the chemical sector. By investigating the input and experiences of the various actors engaged in this development project, this study aims to derive valuable insights into the biomass-to-syngas value chain. It is important to note that the exemplary case of BrigH2 presented in this study serves solely as an illustrative example for portraying the sequential steps and actors involved in the studied value chain. This includes the collaboration between smaller technology firms, like BrigH2, and major chemical firms or clusters such as Chemelot, in the development of sustainable biomass-to-syngas projects. The focus of the study however extends beyond this particular case, encompassing a comprehensive examination of the broader context of the Netherlands and its associated biomass development initiatives and stakeholders.

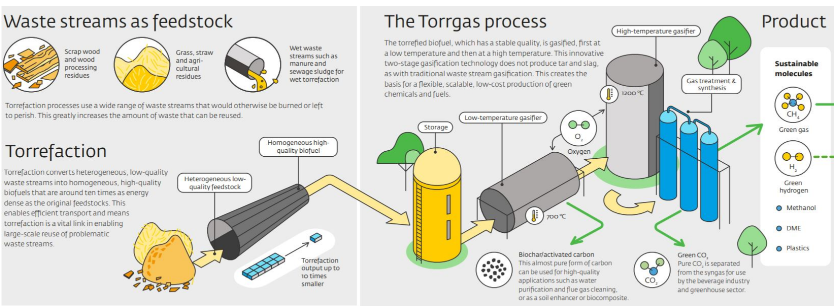

Figure 7: Working principle biomass-to-syngas plant through gasification and torrefaction [26]

3.2 Solution focused chain approach

As explained in section 2 the research methodology of this study primarily relies on the SfSA method as proposed by Zijp et al. and van Bruggen et al.. As can be derived from figure 5, the first two steps of this method focus on data collection. The first step of this research method involved conducting a comprehensive pre-assessment of the value chain. This entails gathering insights from both literature and stakeholder input to gain a holistic understanding of the current state and barriers hindering the widespread adoption of the value chain. The second step focused on prioritising barriers and deriving mutually agreed solutions from stakeholder input with diverse knowledge and experience [68]. However, contrasting to van Bruggen et al.'s research, this study has used different data collection methods. Where the original approach aims to gather most of the industry insights through focus group sessions, this study has opted for a different approach in which eight semi-structured interviews were conducted with stakeholders along the value chain to gather their insights and perspectives on the value chain's development. Additionally, the expert reflection step was constructed as a panel discussion between experts and industry to allow for lively discussions and direct interaction between experts and industry stakeholders. Moreover, as was explained in section 2, in order to improve on the framework as proposed by van Bruggen et al. the Technological Innovation System (TIS)-framework from Ortt & Kamp is introduced to provide a more structured method of researching possible barriers to innovation and diffusion of torrefaction and gasification technology and the biomass-to-syngas value chain. In the subsequent sub-chapters the research method applied in this thesis will be further explained.

3.3 Step 1: Pre-assessment

The initial stage of the Solution-focused Chain Approach involves examining the issue and its surroundings, as well as getting ready for the second collaborative phase [68]. In this way, a variety of perspectives from stakeholders were gathered without any restrictions on understanding all practical, regulatory, or scientific factors. As can be derived from figure 5, the pre-assessment step can be subdivided into three sub-steps which involve an exploratory literature review of the barriers and solutions -, stakeholder analysis -, and stakeholder interviews into possible barrier and solution areas.

3.3.1 Step 1A: Exploratory literature review of barriers and solutions using the TIS framework

3.3.1.1 Search terms and selection criteria

The first step of the pre-assessment stage involved conducting an exploratory literature review into barriers and solutions to the development of the value chain. The information needed to research the barriers and stakeholders that are relevant to Dutch Biomass-to-syngas value chain system is derived from an exploratory literature review of scientific and grey literature together with a stakeholder analysis. The search methods that were used for this exploratory literature review are as follows:

- *Biomass AND (torrefaction OR bio-chemical conversion) AND (biochar OR bio-coal) AND gasification*
- *Biomass AND (torrefaction OR bio-chemical conversion) AND (barriers OR limits OR limitations)*
- *(biochar OR bio-coal) AND gasification AND (barriers OR limits OR limitations)*
- *Gasification AND (syngas OR biofuel) AND applications AND (barriers OR limits OR limitations)*
- *stakeholder AND (representations OR perceptions) AND biomass AND technology*
- *sustainable AND biomass AND (torrefaction OR gasification) AND stakeholder*

These search terms were entered into Scopus to search on title, abstract, and keywords. From the obtained papers a selection was made, through determining their relevance to this research by reading the abstract and conclusion, in addition to this the articles were tested on the following selection criteria. Firstly, only papers published after 2015 were considered in order to make sure state-of-the-art technologies are studied. Secondly, papers needed to have at least 15 citations unless they are published after February 2022, in this case the paper needs to be written by a professor with an h-index of at least 15. Grey literature is found by entering search terms into google. The selection process for grey literature follows the same analogy as that for scientific literature in which the title, abstract and conclusion were scanned on their relevance to the research subject. Moreover, since grey-literature also encompasses documents which entail regulatory and policy information an even stricter criterion for the chronological age of the literature was used, namely only papers from 2018 onward were reviewed. This decision was made to make sure only the latest political and legal perspectives are considered in the research. The reliability of the literature is however not assessed based on the number of citations, but on the publisher of the paper. Only literature originating from knowledgeable and trustworthy institutions such as TNO, SER, IRENA, IEA and governmental institutions are selected. The search terms that were used to find grey literature using google search are as follows:

- (Sustainable biomass conversion OR Biomass upgrading) AND Climate change mitigation AND (bio-economy OR circular economy) AND (Biomass gasification OR Syngas production OR torrefaction)
- (Bioenergy policies OR Biomass policies OR Circular economy policies OR Sustainable development policies OR Bioeconomy strategies OR Waste-to-energy policies)

3.3.1.2 Barrier categorization

The exploratory literature review was explicitly not meant to be exhaustive and aimed to identify a broad set of barriers, such as technological hurdles, rules and regulations, and economic feasibility that served as a starting point to stimulate the consideration of a broad set of viewpoints across stakeholders. Furthermore, the literature review provided the researcher with valuable insights into the challenges and dynamics of the value chain, enabling the development of well-informed and contextually relevant semi-structured interview protocols. This ensured that the interview questions were aligned with the current state of the value chain and effectively captured the relevant issues at hand.
Furthermore, as discussed in section 2, this study builds upon the SfSA framework proposed by van Bruggen et al. by integrating the Technological Innovation System building block framework, as proposed by Ortt & Kamp. This integration enables a more profound analysis and categorization of barriers, intervention strategies, and system dynamics within the value chain. The seven building blocks depicted in table 1 are used to categorise the barriers identified from literature and stakeholder input. These building blocks are formulated such that each of them, once missing, incomplete or incompatible with each other and the innovation, would form a barrier to large-scale diffusion of the technology and value chain. Therefore a complete and compatible set of these building blocks is required for large-scale diffusion of the technologies and value chain. Additionally the barriers were linked to 'influencing conditions' from table 2, which aim to explain the problems in the formation of TIS building blocks and indicate causes of barriers to large-scale applications of an innovation. Furthermore, it is important to note that barriers and influencing conditions are not solely approached from the perspective of policy makers or companies. Instead, the viewpoints of various actors involved in the Dutch biomass-to-syngas value chain were taken into account. Therefore allowing the consideration of multiple perspectives and a more comprehensive understanding of the barriers and influencing conditions within the value chain. Moreover it important to note, that it was not the intention of the researcher to conduct a full TIS analysis on the biomass-to-syngas value chain, however the framework of Ortt & Kamp has rather been used as a structured framework to identify and categorize barriers based on insights from literature and stakeholder research.

3.3.1.3 Defining the value chain & matching methods

Although the incorporation of the TIS building block framework into the SfSA approach as described in section 2 offers a structured approach for categorizing barriers and studying the dynamics of the value chain, it is crucial to establish a precise definition and scope of the Dutch biomass-to-syngas value chain. It is important to note that Ortt & Kamp's methodology primarily focuses on studying the dynamics of an innovation system related to the development of a single innovation, rather than comprehensively analyzing an entire value chain. Therefore, in order to appropriately categorize the identified barriers, it is necessary to modify certain building block definitions and ensure a suitable fit within the context of the specific value chain under investigation. Therefore this section will define the Dutch biomass-to-syngas value chain and its associated actors, which will serve as a basis for subsequent analysis in this thesis.
Porter's traditional concept of a value chain describes the value chain as the full chain of a business's activities in the creation of a product or service from the initial reception of materials all the way through its delivery to market, and everything in between [55]. However in this definition of a value chain Porter reasons from a single company's perspective, whilst this research requires a system's approach fitting to the methods of van Bruggen et al. and Ortt & Kamp. In the research conducted by van Bruggen et al., the term "value chain" is broadly defined as encompassing all stakeholders involved in a product chain of interest. However, this definition lacks specificity with regard to the types of actors included in the chain and the value-adding activities they perform. To provide a more comprehensive understanding of the biomass-to-syngas value chain, we adopt the definition put forth by Panoutsou & Singh, Kircher and Lokesh et al., which define the value chain as a series of sequential and interdependent economic activities, including land use and feedstock production, conversion to energy or bio-based carriers, and finally variable markets that use the end products. This definition recognizes the complexity of the biomass value chain and the cross-sectoral interactions that take place between its upstream and downstream stages, and its actors. Based on this definition of the biomass-to-syngas value chain, a representation of the value chain system has been developed, as depicted in Figure 8. In this simplified representation, the value chain consists of four key steps. The first step involves biomass production, where biomass is cultivated or harvested as a renewable resource. The second step is torrefaction, where biomass undergoes a conversion process to become a tradable commodity. The third step in the value chain is gasification, which involves the production of syngas which serves as a valuable raw material for the production of chemicals. Finally, in the fourth step, the synthesized syngas is utilized to create a diverse range of basic and fine chemicals.

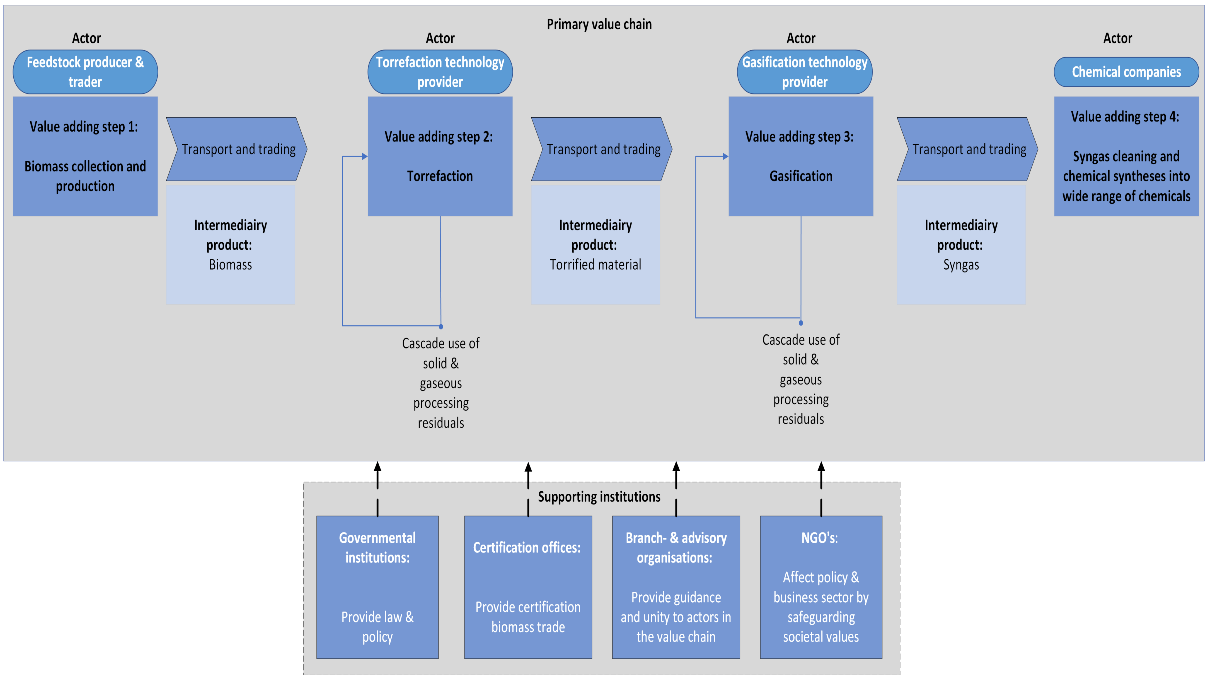

Figure 8: Value chain Biomass-to-Syngas

As mentioned earlier, in order to appropriately categorize the identified barriers, it is necessary to modify certain building block definitions and ensure a suitable fit within the context of the value chain. Particularly, the building blocks related to the characteristics of the product or production system within the value chain were perceived as ambiguous. This ambiguity is caused by the fact that the value chain technically comprises multiple products and production systems, as can be derived from Figure 8.
To address this issue, clear definitions of 'the product' and 'production system' need to be established for this research. These definitions will ensure the appropriate assignment and categorization of the relevant building blocks related to products or production systems within the value chain. Hence, the following definitions for 'the product' and 'production system' will be used throughout this research.

- **The product:** the product in a value chain refers to the final output of the value chain that is delivered to the customer. In the case of the biomass-to-syngas value chain the product is therefore syngas. However since the value chain consists of multiple production steps which produce products that already have stand-alone value as commodities, the intermediates (e.g. raw biomass and torrefied material) are also seen as products. Therefore the building blocks of 'product performance and quality' and 'product price' can also be assigned to the intermediate products of this value chain. [50] [66]
- **Production system:** the production system refers to the set of activities and processes that are involved in creating the product or service, from the sourcing of raw materials to the delivery of the final product to the customer. The production system therefore includes all the value adding activities involved in the value chain, such as production, marketing, distribution, and customer service. The supply chain, but also the technologies of torrefaction and gasification are therefore seen as part of the value chain's production system. [50] [66]

3.3.2 Step 1B: Stakeholder analysis

The second step of the pre-assessment phase requires a stakeholder-analysis to give an overview of the actors active in the development of the biomass-to-syngas value chain for the chemical industry and the subsequent gasification and torrefaction technologies [62]. This step is however not meant to result in an overview of stakeholders and their interests or their stake in the development of the technologies and value chain, but rather serves as a method to find participants for the research process such as the interviews and expert reflection step. Additionally, the identification of stakeholder serves a descriptive function in clarifying barriers encountered by actors involved in the value chain's development, since barriers are to be described from the point of view of the actor that faces the barrier.
As is clear from the previous section, the exploratory literature review combined with the TIS-building block framework already provides an overview of the actors within the innovation system. However since the SfSA research methodology is also dependent on input data from stakeholders itself, derived from interviews and questionnaires, the 'snowball sampling method' will be used to add on the stakeholders found using the exploratory literature review. This method relies on the referrals of research-participants for further research. In this way the sample size of the interviews and questionnaire can be extended. Moreover this method allows stakeholders in the sample to identify relevant respondents for focus groups and expert reflection, thereby providing an industry point of view on who the most essential stakeholders are to involve in the research process[47] [62].

3.4 Step 2: Develop solutions with the value chain

In the solution development phase of this research, the third till seventh sub-questions are answered. As can be derived from figure 5, the SfSA method originally prescribes to set-up focus group sessions with stakeholders from the value chain. These focus groups are aimed at identifying and prioritizing barriers and formulating solutions together with industry partners. An important aspect of a focus group is that participants can respond directly to each other, thereby creating and developing chains of associations, describing personal experiences, and exploring norms and values [62]. Although the use of focus-groups can help gain new insight into the apparent diversity of challenges, perspectives, and opportunities that stakeholders are experiencing and enables actors to consider the whole value chain and discuss innovative solutions cooperatively, it is also a very time-consuming endeavour. Furthermore, during the process of contacting and searching for potential participants, stakeholders expressed a lack of interest in participating in a focus group session. Many stakeholders indicated that the intricacies of the industry were already known to them and a focus group session was not strategically relevant to them. Often stakeholders also indicated to be reluctant to share their strategies or thoughts with industry stakeholders or competitors. As a result, they expressed a general disinterest in engaging in a focus group session. Therefore, in order to obtain a diverse range of challenges, perspectives, and opportunities experienced by stakeholders along the value chain, a decision was made to merge step 1C and 2A of the chain approach (see Figure 5). This was achieved by conducting semi-structured interviews with stakeholders occupying diverse value-adding or supportive roles in the value chain, according to the roles specified in figure 8. By interviewing these stakeholders, a comprehensive understanding of the various challenges, perspectives, and opportunities within the value chain was obtained.

3.4.1 Step 1C&2A: Semi-structured interviews

Semi-structured interviews were performed to collect a wide variety of different sorts of data from actors along the value chain and help expand knowledge on the different viewpoints of actors along the value chain [11]. Semi-structured interviews were selected as the research method as they are well suited for gathering expert perspectives and experiences on a given topic, while providing participants with the freedom to express themselves openly and in depth [5].

The primary objective of these interviews was to identify the barriers that impede the development of the biomass-to-syngas value chain, while also capturing diverse perspectives from the stakeholders involved. Additionally, stakeholders were asked to propose solutions to address the barriers they deemed most significant. Moreover, by asking the interviewees to rank the importance of the barriers that were derived from the exploratory literature review, the interviews gave an initial view of the importance of each barrier and thereby contributed to answering the second, third and fourth sub-question of this research. Moreover, although the interviews were conversational in nature, an interview protocol was used to allow stakeholders to share their views on the value chain's development (see appendix A.1), as well as identify any additional barriers or propose potential solutions. Thereby allowing to extent the list and knowledge of barriers and solutions obtained from the literature review.

As previously mentioned, stakeholders were deliberately selected from different positions and areas of expertise within the value chain. This intentional selection aimed to ensure a comprehensive understanding of industry perspectives regarding the development of the value chain and the barriers hindering the widespread adoption of torrefaction and gasification technologies. By including stakeholders with diverse roles and expertise, the study sought to capture a broad range of insights and gather a comprehensive overview of the challenges faced by the industry as a whole. The stakeholders that participated in the interviews were found using the snowballing method as discussed in section 3.3.2 and from the network of the graduation company Uniper. Interviews were scheduled according to the method described in appendix A.1 and were conducted online via teams.

3.4.2 Step 2B: Questionnaire

In addition to the semi-structured interviews a questionnaire was send to all members that attended the interviews and all relevant actors that were identified in the stakeholder analysis but were unable or unwilling to participate in the interviews. The aim of the questionnaire was to further specify the conclusions from the semi-structured interviews and enable stakeholders to reflect on the prioritized barriers and the assessed solutions from literature [68]. In this way a definitive prioritisation of barriers was obtained. Moreover, participants were asked to rate the viability of solution proposals and provide any additional barriers or solution proposals. Additionally, participants were provided with statements regarding the impact of the implementation of torrefaction technology into the value chain. By rating these statements on their perceived feasibility a more comprehensive understanding of the industry perspective on torrefaction technology was developed, which enabled to review the potential impact and role the technology can have on the development of the value chain.

The questionnaire was made using the Qualtrics program and was tested on content validity by an industry expert to evaluate if the questionnaire items captured the constructs that had to be measured. In total, the questionnaire received 10 responses from industry experts, which indicates additional input was provided by two experts who were not included in the interview population. These additional experts were stemming from consultancy and, commodity trader and energy companies. The overall outline and results of the questionnaire are included in appendix E.

3.4.3 Step 2C: Expert reflection and discussion

Although the input from stakeholders obtained through the questionnaire and semi-structured interviews offered valuable contributions, it is important to note that not all input can be attributed equal weight. Since, industry stakeholders may have vested interests in research and policy outcomes and therefore intentionally influence the results [51]. This is especially relevant in the context of the highly dynamic, small-scale, and innovative environment of the biomass-to-syngas value chain, where the reliability of obtained results can be hindered. Therefore, validation of the obtained results is crucial.

Furthermore, considering the limitations in arranging a traditional focus group session, an alternative approach was developed to enable meaningful engagement and interaction among stakeholders and experts. This involved hosting an online webinar designed to facilitate an expert reflection session through lively discussions and real-time polling with industry stakeholders. This webinar was hosted on the Biomassafeiten platform, which is a platform led by companies and organizations active in the biomass industry with the aim of creating support for sustainable biomass utilization across various sectors. The webinar, was presented on Microsoft Teams with PowerPoint slides and lasted approximately one hour and encouraged participants to actively contribute to discussions by unmuting themselves and sharing their thoughts. To further facilitate participant interaction and feedback, the webinar utilized the Slido program. Participants were able to provide ratings on the feasibility of solution proposals through real-time polling, and the results were displayed on the presentation screen, providing a visual representation of the diversity of opinions among participants. This helped in setting the stage for the subsequent panel discussion.

The webinar was structured as a panel discussion, featuring industry experts with diverse backgrounds, including a gasification technology developer, a consultancy representative, and a government official. This diversity of expertise amongst the panel of experts was purposely selected to allow for different perspectives and a broad view on the proposed solutions. Additionally approximately 35 participants from the industry also attended the webinar, of which 21 participants actively engaged in the discussion and live polling to evaluate the feasibility of the proposed solution statements.

The webinar was designed such that the the most pressing barriers were presented together, and a comprehensive solution proposal was formulated to address these barriers. This approach enabled experts and industry stakeholders to respond to barriers, evaluate the feasibility of the solutions, provide nuanced insights into the proposed solution areas, and even propose additional solution areas. Moreover, by incorporating literature, survey input, and stakeholder perspectives gathered from interviews, the proposed solution was evaluated in a more robust and comprehensive manner compared to van Bruggen et al.'s original methodology, which solely relied on assessing solutions from literature with stakeholder input. As a result, a more holistic and informed evaluation of the proposed solution was achieved.

In appendix F the detailed documentation of the webinar is implemented, including the solution statements, panel-discussion transcripts, and additional stakeholder statements. The analysis of the webinar followed an interpretive approach inspired by Bakker et al., where the key topics and findings discussed by each expert are summarised. Based on this summary a narrative was then crafted to capture the experts' viewpoints on the solution proposals and provide an overall assessment of their feasibility. Furthermore, the narrative captures nuances and potential improvements to the proposed solutions as suggested by the experts. Additionally the feasibility ratings from the real-time polling are depicted. Overall, this method of hosting an online webinar, engaging stakeholders, and evaluating proposed solutions through discussion and analysis lead to a more comprehensive and informed assessment of the solution proposals, thereby aligning with the goal of achieving "mutually agreed solutions through discussion and learning" [62].

3.5 Interview Analysis: Iterative Analysis & Content Analysis

As discussed in section 3.4.1, the semi-structured interviews were conducted to collect a wide range of data from stakeholders at different stages of the value chain. To increase the validity, every interview was recorded, and transcribed word-for-word immediately after the interview was conducted as recommended by Bougie & Sekaran. From these transcripts the aim was to identify barriers and solutions, and formulate a comprehensive understanding of the perceptions and views of both stakeholders and organizations regarding the development of the value chain. Therefore a three stage iterative analysis process inspired by Bocken & Geradts's approach was employed to analyze the interview data. Moreover content analysis was included in the second analysis step to determine the frequencies in which barriers cause failures in TIS building blocks that hinder the development of the biomass-to-syngas value chain and torrefaction technology.

As depicted in Figure 9, the analysis method employed in this study consists of three iterative steps: open coding, axial coding, and selective coding. Prior to performing the coding process, the interviews were transcribed in Word and carefully read to gain a general understanding of the themes that emerged from the interviews. Additionally, the last two steps of Denscombe's method of content analysis were used in conjunction with the iterative coding method. These steps involve determining the frequency of failures in certain building blocks and analyzing their relationships from the described barriers. The three step iterative analysis process is therefore used to identify barriers and solutions from the interview transcripts and form a holistic of stakeholder perspectives, whereas content analysis is used to determine the extent in which certain building blocks in the value chain are lacking.
During the first step of the open coding process, important lines, words or quotes were obtained from the transcripts as 'interview terms' which represent a specific concept, idea, or phenomenon found in the data. These open codes include statements of interviewees which specifically describe a barrier or solution as well as phrasings which implicitly point to a certain barrier or solution. For instance, consider the interview terms "Maatschappelijk debat belemmering opzet waardeketen" (societal debate hindering value chain development) and "negative framing." Both terms point to the same barrier, which is 'the lack of political consensus regarding biomass and its subsequent impact on policy decisions concerning biomass-to-chemistry'.
In the second stage of data-analysis open codes are grouped into axial codes which aim to form more abstract and theoretical categories, and represent the barriers and solutions in this thesis. Overall grouping these interviews into axial codes resulted in obtaining a list of 37 barriers and 18 solutions to the development of the value chain. These barriers are compared to and grouped with barriers stemming from the exploratory literature review and categorised according to the methodology described in subsubsection 3.3.1. In this way an all encompassing list of barriers to the development of the biomass-to-syngas value chain and torrefaction technology was developed. Additionally, using conceptual content analysis insight was created into the most predominant building block failures by establishing the existence and frequency of the categories. Moreover, the relationship between barriers was analysed by examining the respective influencing conditions which caused failures in building blocks. This analysis helped to understand the interconnections and dependencies between the barriers, providing insights into how certain conditions or factors contribute to the occurrence of failures in specific building blocks.
In the final stage of the analysis, selective coding was used to identify overarching themes and sub-themes that establish connections between barriers and solutions, and clarify their interrelationships. The sub-themes provide a description of the interconnectedness between specific barriers and solutions, while the themes aim to encompass the broader category to which these barriers belong. For instance, the sub-theme of 'policy failures' illustrates how barriers such as slow and complicated licensing processes and the absence of subsidy schemes contribute to a lack of investments in the industry, thereby impeding the overall development of the market. Overall, the analysis of these overarching themes and sub-themes enables a comprehensive exploration of how stakeholders perceive the development of the value chain. Moreover, following the method of Braun & Clarke, important stakeholder perspectives and narratives are incorporated into the analysis, thereby strengthening the theoretical understanding and facilitating the inductive formation of theories regarding the development of the biomass-to-syngas value chain and the implementation of torrefaction within it.

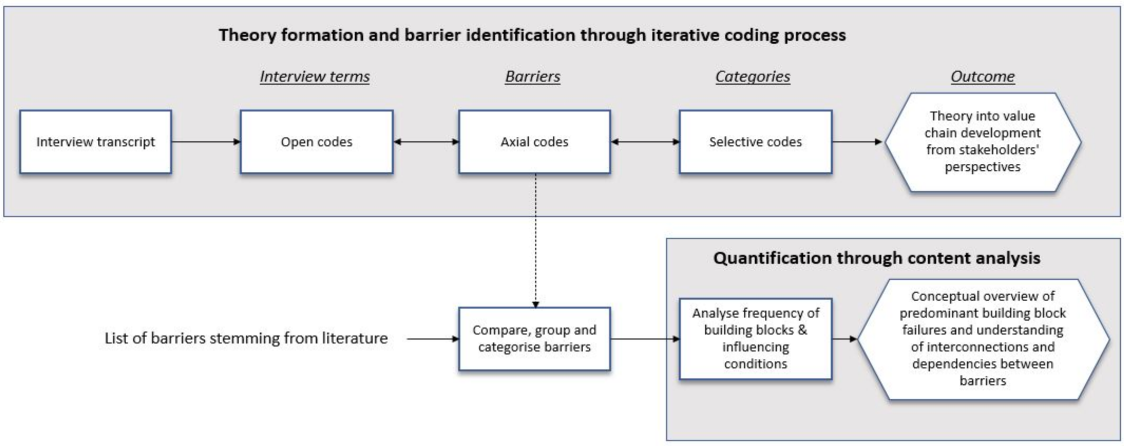

Figure 9: Data analysis methods

3.6 Summary of research method

While the SfSA method by van Bruggen et al. has served as the foundation for this research methodology, certain adaptations have been implemented to ensure a more suitable alignment with the studied value chain and technologies. The following figure provides an overview of the research steps undertaken in this study and the corresponding outcomes.

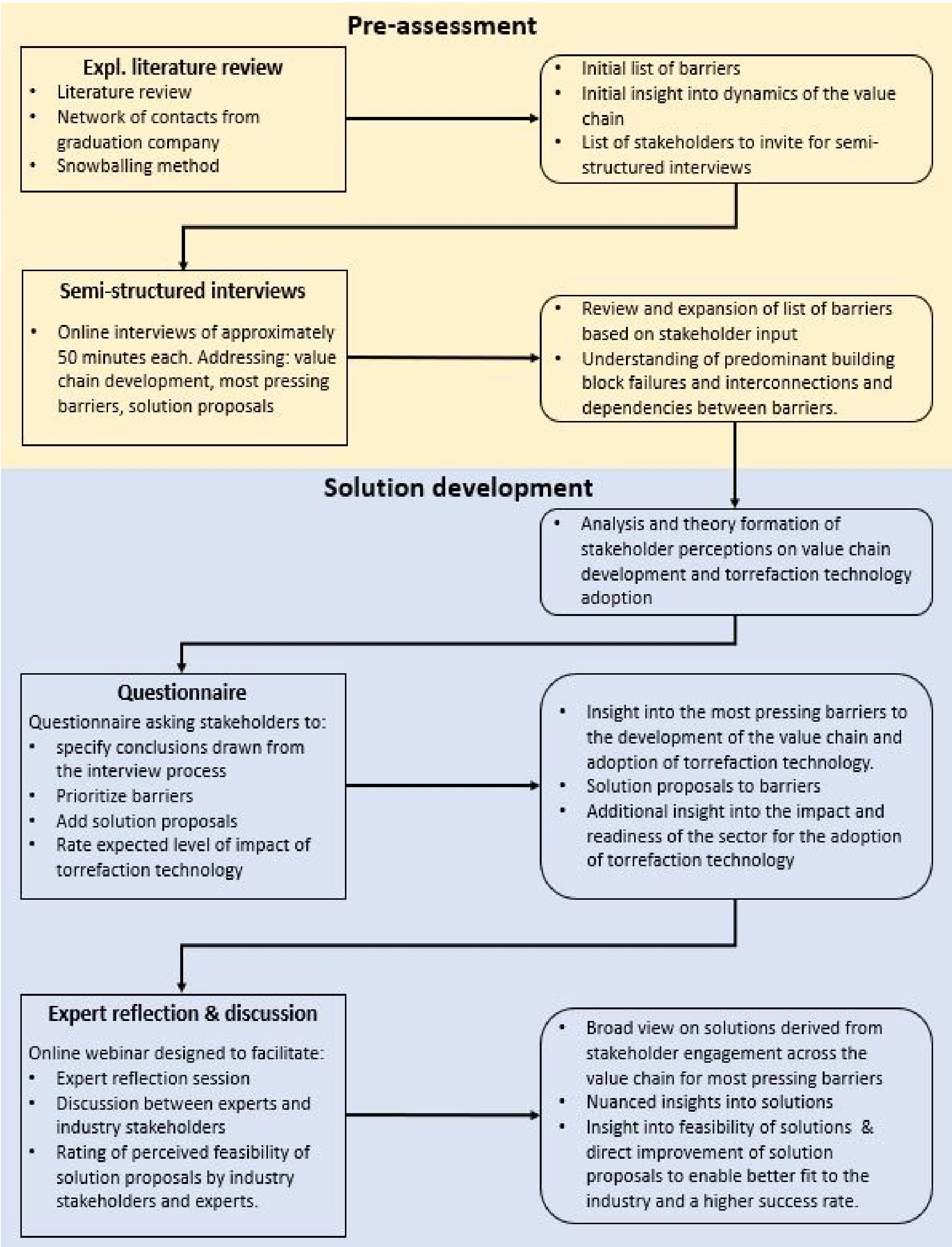

Figure 10: Overview research methodology

4 Step 1B: Stakeholder analysis

4.1 Actors from literature

As described in section 3.3.2 an overview of relevant actors was derived from the exploratory literature review combined with the TIS-building block framework.
The type of actors active in this value chain can be specified based on the innovation system framework of Bergek et al. and the defined value chain in figure 8, which specifies actors in an innovation system do not only include firms but also universities and research institutes, public bodies, influential interest organizations (for instance NGO's), private financiers and standardisation organisations [7]. This perspective is supported by research of the Dutch Environmental Assessment Agency (PBL)(Strengers & Elzenga), which has identified the main stakeholders in the Dutch biomass industry as the business sector, branch organisations, knowledge institutions, governmental institutions, certification offices and NGO's [59]. Moreover a deeper understanding of the value chain system can be gained, when we connect these actors to the four structural components of a TIS as proposed by Ortt & Kamp. In this context, the following structural components should be present in the value chain system: Technology, a network of actors, Supporting institutions and a demand side.
The structural component 'technology' is represented by the gasification and torrefaction technologies employed in the value chain. These technologies enable the conversion of biomass into syngas and the subsequent synthesis of chemicals.
The network of actors within the value chain includes biomass traders, technology developers, universities, and research institutes. Biomass traders play a critical role in facilitating the trading and supply of feedstock, while technology developers contribute expertise in advancing gasification and torrefaction technologies. Universities and research institutes also play an important role by conducting scientific research, fostering innovation, and providing knowledge and resources to support the value chain.
Supporting institutions, including governmental bodies, certification offices, branch- and advisory organizations, and NGOs, form another crucial component of the value chain system. These institutions provide support, regulations, certifications, and guidance to ensure the smooth functioning and sustainability of the bio-based value chain. Their involvement is essential for creating an enabling environment for the value chain's development and growth.
Lastly, the demand side of the value chain is represented by the chemical industry, which serves as a significant consumer of the diverse range of basic and fine chemicals produced through the synthesis of syngas. Moreover external investors also represent the demand side.
The business sector, as identified by the Strengers & Elzenga, along with branch organizations, certification offices, and governmental institutions, actively participate in shaping and driving the value chain. Therefore the actors discussed in this section will contribute to describing the barriers to value chain development from the perspective of the actors who experience these barriers. These barriers are outlined in the comprehensive list of barriers that were obtained in this study, which can be found in Appendix C.1.

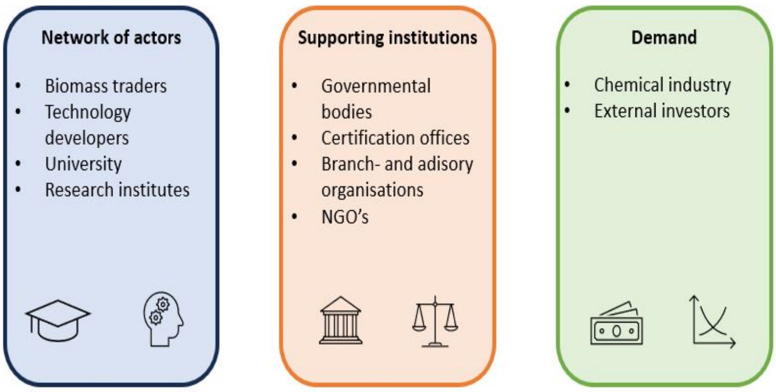

Figure 11: Actors used in barrier description process

4.2 Participant overview

In addition to the actor groups discussed in the previous section, the snowballing method was used combined with the network of the graduation company Uniper to identify and obtain relevant participants for the semi-structured interviews, questionnaire and expert reflection session. Through this approach, eight stakeholders were found that participated in the semi-structured interviews. However, it should be noted that a ninth stakeholder, who initially participated, later expressed a desire to retract their response and is therefore not included in this research. These eight stakeholders are listed in table 3 below. To safeguard the privacy of the stakeholders, their names have been excluded from this study, instead they are referred to by a reference code in the thesis.
This overview clearly indicates that the interviewed stakeholders encompassed multiple stages of the value chain, including value-adding activities, such as biomass traders and technology providers for both torrefaction and gasification. Additionally, stakeholders from supporting institutions, including advisory organizations, independent research institutions, and certification and government advisory bodies, were also involved. This diverse representation across different stages of the value chain ensured a comprehensive perspective and incorporated a wide range of expertise and insights from key industry players.

#	**Reference in this thesis**	**Organisation & profession**	**Function in value chain**
1	[A]	Biomass sourcing - Uniper	25 years of experience in biomass trading both in local as well as in international biomass streams.
2	[B]	Scientist torrefaction - TNO	Development of knowledge for the industry. Involved in several (demo-) projects which focus on coupling torrefaction technology to production processes of companies in diverse industries including the chemical sector.
3	[C]	Senior climate scientist - PBL	Government advisory organization which influences government policy and conducts independent value chain research. The interviewee has over a decade of experience in the biomass sector and climate policy.
4	[D]	CEO syngas start-up - BrigH2	start-up in syngas production through the gasification of torrefied biomass which is currently developing a demo-plant on the Chemelot campus to produce bio-based syngas for the chemical industry.
5	[E]	Torrgas	Syngas technology developer based on torrefied biomass. Amongst the first companies to have successfully launched a viable demo-plant. Moreover the company puts great emphasis on the exploitation of by-products such as biochar to improve the business case of its gasification process.
6	[F]	Project manager - Yilkins	Torrefaction technology developer which has developed a modular system for Biomass Conversion.
7	[H]	Principal consultant and Business Lead Emerging Energy Technologies - DNV	DNV provides expertise and support to stakeholders in the biomass sector to ensure compliance with regulations, standards, and best practices. Additionally the interviewee was involved in writing advisory reports to the government in regard to policy formation for the biomass sector.
8	[G]	Manager business development - Gidara	Gidara is a technology developer of gasification technology, which makes syngas from waste-streams. The company currently is building its first production facility for the production of sustainable methanol. Furthermore its production facility will also be home to a testing facility, knowledge centre, and pilot plant in order to allow for the further development of gasification technology.

Table 3: Interview stakeholders

The industry experts for the webinar and expert reflection session were recruited through the extensive network of the 'Biomassafeiten' platform. Special attention was given to identifying an expert in the field of policy and subsidy formation, as it was observed during the stakeholder analysis process that there was a lack of awareness and knowledge regarding gasification and torrefaction technology within such institutions. Additionally, an expert from the VNCI specialized in sustainable material transition was planned to participate in the expert panel discussion. Unfortunately, due to unforeseen circumstances, this expert had to cancel at the last minute. As a result, the panel of experts for the session consisted of the three individuals listed in the table below. Each expert possessed a minimum of five years of experience in their respective current professions and areas of expertise. Furthermore, they had all accumulated at least a decade of overall experience within the biomass sector, demonstrating their knowledge and understanding of the subject matter.

Name	**Expertise**	**Organisation & profession**	**Function in value chain**
Sander Peeters	Sustainable raw materials and fuels, sustainable industry	Advisor sustainability at RVO	Subsidy- & policy
Robin Post van der Burg	Torrefaction & gasification technology	Torrgas - CEO & owner	Technology development
John Bouterse	Business consulting across the entire value chain	Twinnovate - CEO	Consultancy

Table 4: Members of the discussion panel and their expertise

5 Step 1A: Identification of barriers

Using the search terms specified in section 3.3 scientific and grey literature was found regarding the biomass to syngas value chain and torrefaction. This resulted in finding a list of 15 scientific sources and 16 gray-literature sources regarding the the development of the biomass to syngas value chain and the integration of torrefaction technology in this value chain, which are shown in appendix B. These sources were reviewed in-depth to identify barriers to the biomass-to-syngas value chain and torrefaction technology. The review was conducted iteratively, wherein barriers from various sources were consistently compared to identify similarities and differences in order to merge or separate these barriers. This iterative process led to the discovery of 35 barriers, with 26 pertaining to the biomass-to-syngas value chain in general, and 9 specifically related to torrefaction technology.

To enhance contextual understanding and facilitate categorization of the barriers based on TIS-building blocks and influencing conditions as described in section 2, the barriers were briefly described and listed in appendix C.1. This list of barriers was reviewed and extended on the basis of stakeholder input from semi-structured interviews and the questionnaire (see appendices C.2, D and E), as discussed in section 3.4. During this process, it was found that five barriers were identified in the first phase of this research, which were not recognized or mentioned in the stakeholders' discussion on solution opportunities during the second phase. These barriers are detailed in table 5 below. During the stakeholder discussions, it was found that some of these barriers were not seen as barriers to the development of the value chain, as stakeholders indicated that their industry or company had already successfully addressed these barriers. For instance, barrier #42 was recognised by stakeholders as a well known problem to the development of torrefaction technology during initial phases of torrefaction technology development, however present-day torrefaction projects and initiatives appear to have effectively addressed this concern.

Notably, barrier #41 regarding the coal-like properties of torrefied material was actually not perceived as a barrier but as a solution. Stakeholders indicated that the logistical advantages stemming from these coal-like properties would enhance the supply-chain and cost-effectiveness of the biomass-to-syngas value chain. The self-heating problem was therefore not seen as a barrier to the development of torrefaction technology, as existing solutions from the coal industry already address this concern.

#	**Barrier**
9	There is uncertainty regarding the extent to which nations can create additional criteria and legislation at the national level regarding the importation and certification of biomass, causing national policies to lack the customization required for their case/region
19	The production of sustainable biomass can have negative (and sometimes positive) consequences for biodiversity
40	Lacking regulatory framework regarding the distribution and processing of 'waste-streams' and torrified materials, increasing the complexity of setting up the supply chain of waste-to-x projects
41	Self-heating problem: Torrefied material has coallike properties, thereby increasing the odds for self-ignition. Storage facilities have to be adjusted for this phenomenon creating different supply chain dynamics than for 'normal' biomass
42	Process interruptions occur frequently due to technical challenges in achieving constant and well-controlled process conditions for the production of a uniform product

Table 5: Barriers not mentioned or recognized by stakeholders

The solution-focused approach resulted in another key finding, namely that the stakeholder discussions and interviews lead to identifying nine additional barriers to the development of the biomass-to-syngas value chain, which are described in table 6 below. Apart from barrier # 26 all other added barriers either described a failure of the TIS-building block 'network formation and coordination' or 'innovation specific institutions' (see Appendix C.1). This is a strong indicator that stakeholders perceive barriers that are withholding the development of the value chain are stemming from obstacles in terms of legal and regulatory compliance, as well as establishing and managing effective partnerships, thereby indicating a complex and fragmented business environment. In addition barrier #25 shows how uncontrollable circumstances such as the Ukraine war can affect the network formation amongst actors in the value chain. Overall, the addition of these barriers resulted in a list of 44 barriers to the development of the biomass-to-syngas value chain of which 9 barriers are to torrefaction technology specifically.

#	Barrier
23	Technology providers of gasification projects are unable to obtain long-term feedstock contracts, due to their limited market share, which are needed as leverage to attract external investors
24	The lack of investments in gasification projects withholds growth of this sector and subsequently the possibility of obtaining long term feedstock contracts.
25	Ukraine war led to increased uncertainty and material prices resulting in a wait-and-see mentality amongst investors
26	Competition of electrolyser technology in hydrogen projects results in lacking investments. Since electrolyser technology obtains more subsidies and is a less uncertain investment in the political sense.
27	Due to limited market power biomass-gasification projects are unable to impose the required sustainability demands, thereby preventing the build up of secure and sustainable supply chain and new partnerships
28	The singular emphasis on sustainability has led to an excess of regulations and certifications flooding the market, which has made the value chain more complex to build.
29	Complicated and slow permitting schemes slow down projects and form a administrative and financial barriers for SME technology providers
31	The term 'biomass' is much to broad and has a negative stigma. Thereby not allowing for the distinction of sustainable feedstock streams and negatively contributing to the public image of biomass.
32	Lack of trained technical personnel hampers technology development

Table 6: Barriers which were additionally mentioned by stakeholders

5.1 Innovation system performance

As described by the research method in sections 3.3.1 & 3.5, the barriers in table 9 in appendix C.1 are categorised according to the TIS building blocks they form a barrier to and the influencing conditions which cause or influence these barriers to exist. This categorization enables to gain a deeper understanding of the barriers affecting the large-scale diffusion of gasification and/or torrefaction technology and the successful development of the biomass-to-syngas value chain [48]. Additionally, the prevalent influencing conditions that contribute to the occurrence of these barriers can be determined. By examining the interaction between the influencing conditions and the lacking building blocks a comprehensive view of the specific building blocks that predominantly cause a hindrance to the development of the biomass-to-syngas value chain and torrefaction technology can be created. This analysis thereby also provides an understanding of the prevalent 'influencing conditions' responsible for causing these barriers to occur.
In figure 12 below an overview is given of the distribution of the building blocks which are affected by the barriers as described in appendix C.1. The distribution clearly shows that the majority of barriers cause failures in the building blocks; 'production system', 'innovation specific institutions' or 'network formation and coordination', as the barriers pertaining to these building blocks account for %80 of all barriers that were found. This therefore indicates that the 'solution space' mainly evolves around these three building blocks. However it is important to note that a single barrier is still capable of halting the large-scale diffusion of the biomass-to-syngas value chain. Therefore all barriers should be considered as significant to the development of the value chain and effective solutions should therefore address various barriers simultaneously [62].

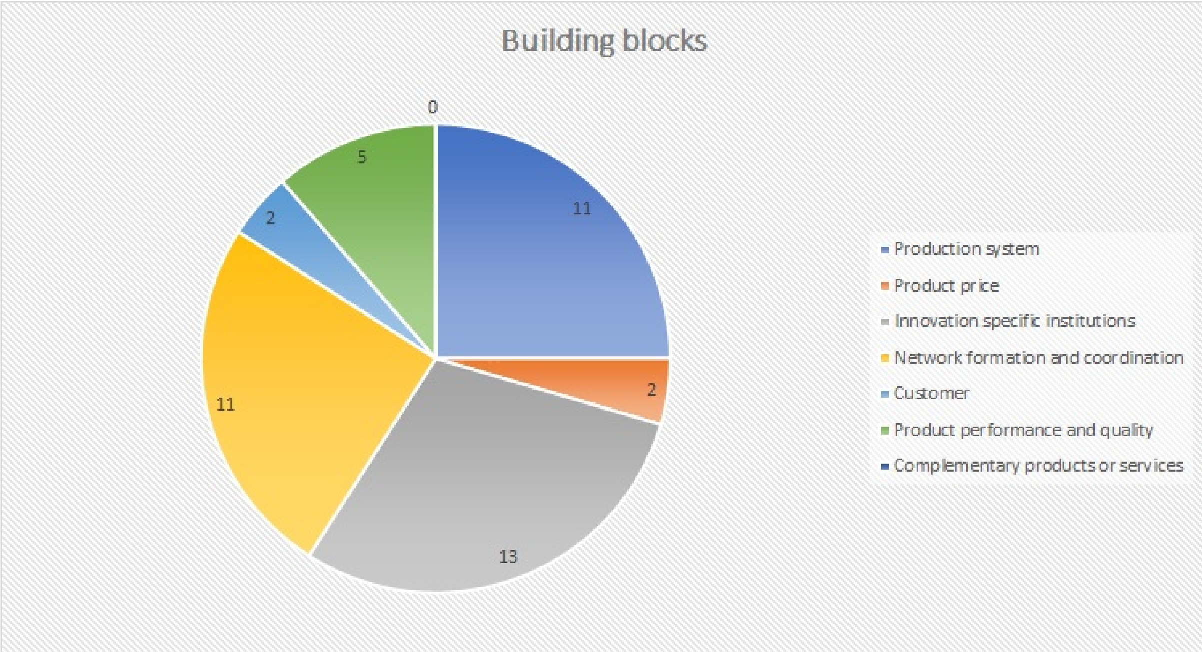

Figure 12: Overview TIS-building blocks

5.1.1 Building block failures & Influencing conditions

In order to address the identified barriers effectively and formulate fitting solutions to them, more information is needed regarding the root cause of these barriers. Therefore it is essential to analyze the influencing conditions related to each barrier, as they subsequently lead to failures in the TIS-building blocks. Hence, the relationship between the influencing conditions and TIS-building blocks derived from the barriers described in appendix C.1 is characterised in figure 13 below. The figure clearly illustrates that the influencing conditions leading to decreased performance of building blocks are widely dispersed. This highlights the necessity for a comprehensive solution that addresses multiple influencing conditions to rectify the deficiencies in a building block.

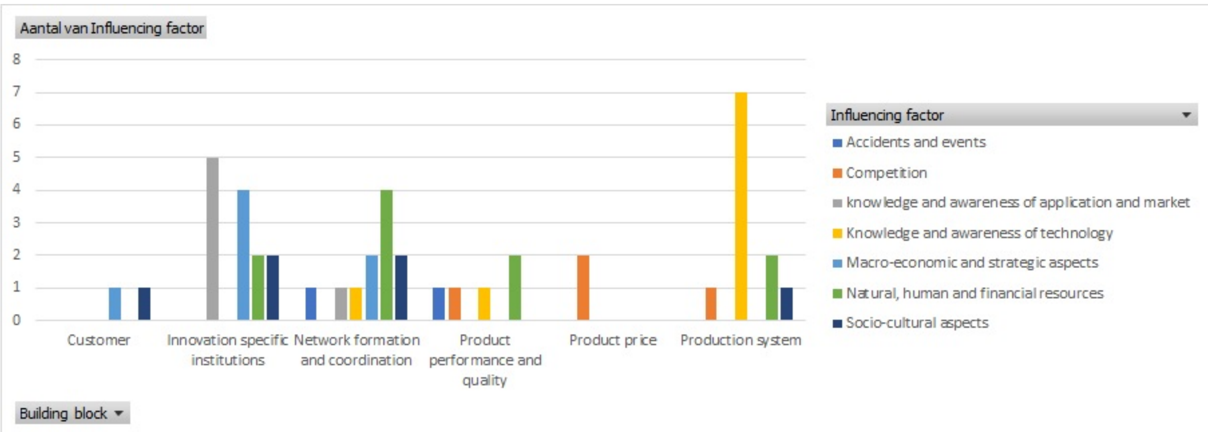

Figure 13: Relationship Building blocks vs. influencing conditions

5.1.1.1 Production system

The building block 'production system' is significantly affected by failures in the influencing condition of 'knowledge and awareness of technology'. This clearly indicates that there is a lack of both fundamental and applied technological knowledge in the innovation system of the biomass-to-syngas value chain. Consequently, failures occur in the production system which make it unable to deliver high quality products in large quantities against competitive costs. These failures arise in both the gasification as well as torrefaction technology, barriers #1, #2, #36 and #42 clearly show how both technologies struggle in producing high quality products from varying biomass feedstock streams. In addition, barriers #33 and #44 highlight that the lack of technical knowledge results in low technological maturity and a lack of knowledge regarding the up-scaling of the technologies, resulting in high technological risk. Moreover, barrier #38 shows how this lack of technical knowledge in the value chain system specifically results in operational issues in torrefaction technology, thereby impeding the implementation of this technology into the biomass-to-syngas value chain.

The high technological risks associated with the torrefaction and gasification technologies subsequently cause another barrier to occur, namely barrier #30, in which there is a lack of natural, human and financial resources due to investors' hesitancy. This finding demonstrates how barriers within one building block can lead to cascading failures in other building blocks, aligning with the findings of Kirchherr et al.'s study on barriers to the circular economy. This study revealed that barriers can be interconnected and interact with each other, thereby creating a network of challenges. Another notable barrier in the production system, stemming from the scarcity of natural resources, is barrier #18. This barrier highlights a failure in the supply chain, specifically the limited availability and possibilities of local sustainable biomass production for use in the biomass-to-syngas value chain.

The production system within the value chain not only encounters obstacles in acquiring sufficient resources due to technological risks or supply chain failures, but also faces competition from alternative products. Barrier #26 highlights the impact of substitute technologies, such as electrolyser technology, which can impede the progress of biomass-to-syngas projects. These substitute technologies have the potential to attract subsidies and investments intended for hydrogen to chemicals projects, diverting them from biomass-to-syngas initiatives. In addition, the prevailing political uncertainty surrounding biomass utilization is increasing concerns about its potential negative consequences for biodiversity (barrier #19), which further contributes to this diversion of resources. As a result, the development of biomass-to-syngas projects faces additional hurdles in the form of limited financial resources due to competition from alternative technologies and socio-cultural aspects regarding sustainability concerns.

5.1.1.2 Innovation specific institutions

The influencing conditions leading to a failure in the building block 'innovation specific institutions' are widely dispersed. The primary causes of these barriers can be attributed to either a lack of knowledge and awareness of application and market or macro-economic and strategic aspects. Additional reasons for a failure in 'innovation specific institutions' include a scarcity of natural, human, and financial resources, as well as socio-cultural aspects.

Regarding macro-economic and strategic aspects, barrier #6 addresses the absence of long-term policies specifically tailored to the chemical sector within both the European Union (EU) and the Netherlands (NL). This lack of long term policy is subsequently reflected in barrier #22, which highlights the limited carbon pricing regulations specifically aimed at the chemical industry. These two barriers were frequently mentioned by both stakeholders and literature, and result in insufficient investments in the biomass-to-syngas value chain, which hinders its overall development.

Due to a lack of knowledge and awareness of application and market amongst stakeholders in the value chain, five barriers occur which result in a failure of the building block of innovation specific institutions. Of these five barriers, barrier #31 was added through stakeholder discussion as an important barrier to the development of the value chain. Stakeholders described how the general term 'biomass' combined with the negative image regarding biomass usage is partly responsible for causing a public debate surrounding biomass usage which has resulted in lacking certification and subsidy schemes regarding syngas production (barrier #5), lacking investments in the value chain (barrier #11), and limited policy attention regarding torrefaction and gasification technologies (barrier #12).

Socio-cultural aspects lead to the occurrence of barriers #11 and #28, in which the norms and values held by stakeholders in the socio-technical system regarding sustainability and climate change has resulted in an excess of regulations and certifications, which has made the value chain more complex to build and investors hesitant to invest in the development of new projects.

The lack of natural, human, and financial resources can best be attributed to the absence of innovation-specific institutions, rather than being the cause for the lack of innovation specific institutions. Once again showing how a failure in a TIS building block can lead to additional failures in other parts in the innovation system. Barriers #29 and #34 both describe a situation in which either complicated and slow permitting schemes or inadequate subsidy schemes result in slowing down projects and withholding investments in the value chain.

5.1.1.3 Network formation and coordination

Failures in the building block 'network formation and coordination' can be attributed to a wide range of influencing conditions, with barriers arising from 6 out of the 7 identified influencing conditions. The predominant cause for a failure in the building block stems from a lack of natural, human and financial resources, followed by macro-economic and strategic aspects, and socio-cultural aspects.
One major hindrance to network formation between chemical firms, technology providers, governmental institutions and feedstock suppliers is caused by political uncertainty and fast evolving climate policies which lead to insufficient investments in the industry and limited formation of partnerships (barrier #13). The lack of financial resources within the value chain have further restricted the availability of natural resources by preventing technology providers from securing long-term feedstock contracts, thereby impeding sector growth (barriers #23 & #24). Additionally, the shortage of trained technical personnel represents a lack of human resources available to the value chain (barrier #32).
Apart from a scarcity of resources, macro-economic and strategic aspect also represent a barrier to the development of this building block. For instance, barrier #27 describes how technology providers and chemical firms are unable to impose the required sustainability demands on their feedstock supplier due to limited market power, thereby preventing the build up of secure and sustainable supply chain and new partnerships. Barrier #20 further explains the insufficient connection between the agricultural and chemical sectors, resulting in an absence of partnerships between these actors and a discrepancy between sustainable biomass production and bio-chemical innovation projects.
Socio-cultural aspects are another cause for the limited network formation and coordination amongst stakeholders in the value chain. According to barrier #7, companies perceive existing subsidy and certification schemes as unreliable and impractical, discouraging their participation in the value chain. Moreover, high political uncertainty arising from a polarized public debate further hampers policy attention towards torrefaction and gasification technology development (barrier #12). Consequently, socio-cultural aspects, including the public debate and company perception, exert substantial influence on the formation of reliable and practical policies, impeding stakeholder engagement and network formation.
Lastly the influencing conditions of knowledge and awareness of the technologies amongst stakeholders and the occurrence of accidents and events pose potential barriers to network formation and coordination amongst actors in the supply chain. According to barrier #35, the market for torrefaction and gasification technology providers is currently characterized by a limited number of small-sized manufacturers. Consequently, other key stakeholders, including investors, chemical firms, and feedstock suppliers, remain unaware of these technologies and the potential opportunities they offer, causing network formation to hamper. Additionally, the occurrence of the Ukraine war has led to increased market uncertainty and volatile material prices, creating a wait-and-see mentality among investors and chemical firms, which impedes the formation of strategic partnerships (barrier #25).
Overall, these influencing conditions and barriers underscore the complexities surrounding network formation and coordination in the value chain, emphasizing the need for comprehensive strategies to overcome these challenges.

5.1.1.4 Product performance and quality

The TIS building block 'product performance and quality' faces various challenges resulting from the identified barriers. Barriers #16 and #17, related to natural, human, and financial resources, highlight the characteristics of raw biomass feedstocks as a barrier to establishing a viable and stable supply chain. One major barrier is the limited ability to secure reliable feedstock of consistent quality due to heterogeneity and nonavailability of feedstock (#16). Additionally, the expensive supply chain poses a significant obstacle, influenced by factors such as the large bulk size, seasonal dependence, and limited storability of raw biomass (#17). As described in subsubsection 1.2.1, torrefaction can improve biomass properties by making the feedstock more homogeneous and improving its transportation characteristics. However, the integration of torrefaction technology into the biomass-to-syngas value chain also comes with its own barriers. For instance, the product performance and quality of torrefied biomass is challenged

due to the increased content of inorganic compounds and ash formation during torrefaction, which limits its utilization of torrefied biomass in gasification and combustion practises (barrier #37). This barrier comes forth from a lack of knowledge and awareness regarding the application of torrefaction technology in gasification processes. Furthermore, torrefied biomass faces competition from substitute products such as raw biomass in post-processing, as it is more difficult to densify and pelletise leading to higher operational costs in comparison to raw biomass processing (barrier # 43).
Collectively, these barriers contribute to the challenges faced by the 'product performance and quality' building block, impeding the development and utilization of torrefaction technology in biomass-to-syngas value chains.

5.1.1.5 Customer

Chemical firms were rarely described as a disruptive party to the development of a biomass-to-syngas value chain in the stakeholder process. Stakeholders described that the prevailing climate policies at both the EU and national level are compelling companies to strategically explore and invest in more sustainable production methods. However, despite this consideration the stakeholders still described an underdeveloped market for biomass-to-syngas projects (#35) and limited investments in the industry (#24). This can partly be attributed to the path dependency observed in chemical firms, where significant investments have already been made in existing technologies and supporting infrastructures. The continued adoption of these established technologies or processes is often associated with growing benefits [39]. Barrier #21 identifies this macro-economic and strategic failure, where stakeholders described how chemical companies can be hesitant to invest and cooperate in sustainable chemical production projects due to path dependency and concerns regarding potential knowledge spillovers. Moreover, this path dependency is further maintained by the socio-cultural issue described by stakeholders and highlighted by CPB in barrier #14. In which there is described how limited circular behaviour among chemical firms is maintained due to a business model of short term profit seeking and obligatory dividend payments to shareholders is.
Overall, while chemical firms have been acknowledged as willing to invest in bio-based technologies, barriers #14 and #21 collectively demonstrate how both macro-economic and strategic aspects, as well as socio-cultural aspects, can still hinder investments in the development of the biomass-to-syngas value chain, leading to a failure in the 'customer' building block.

5.1.1.6 Product price

As is clear from Figure 13, the barriers associated with product price can both be attributed to competition posed by substitute products. In barrier #3 stakeholders and literature describe how biochemicals produced through gasification of (torrified) biomass is still unable to compete with fossil-fuel based chemicals. Although this issue can be attributed to various factors, including the expensive supply chain and technological complexities associated with the production of bio-based chemicals from (torrified) biomass as discussed in earlier sections 5.1.1.1 and 5.1.1.3. Stakeholders have also raised concerns regarding the limited policy attention and absence of carbon pricing specifically targeted at the chemical industry (see 5.1.1.2), thereby resulting in an unfair competitive advantage for fossil-based chemicals over bio-based alternatives. Barrier #3 therefore represents a multifaceted issue regarding the viability of the biomass-to-syngas value chain.
Additionally, barrier #39 highlights how torrefied pellets are currently more expensive than incumbent wood pellets. This price difference presents a significant challenge for torrefaction technology, as it faces competition not only from fossil-based value chains but also from the existing bio-based value chain. However, it is worth noting, that some stakeholders have debated that the purchase costs of torrefied pellets can be compensated by the improved logistics and enhanced gasification characteristics the product offers over raw-biomass feedstock.
In conclusion, barriers #3 and #39 convey how the biomass-to-syngas value chain and integration of torrefaction technology within it still faces challenges in offering economically viable alternatives to fossil based chemicals. Overcoming these obstacles is crucial for the successful development and widespread adoption of sustainable solutions in the chemical industry.

5.1.1.7 Complementary products or services

Based on the findings presented in Figure 12, there can clearly be derived that no barriers were identified which are related to the building block of complementary products or services. This can be attributed to the fact that the production of chemicals from syngas is already a well-established technical process. Notably, established methods such as the water-gas shift reactor for methanol production or the Fischer-Tropsch process for hydrocarbon production are widely recognized in the chemical industry [25] [35]. Consequently, the integration of biomass gasification for syngas production and subsequent chemical synthesis is generally considered feasible and not perceived as problematic. However both literature and stakeholders have highlighted the importance of addressing the existing challenges surrounding syngas quality from biomass gasification to ensure successful integration into chemical production processes, as discussed in sections 5.1.1.1 and 5.1.1.4 (barriers #1, #2, #16, #36 and #42). Addressing these inconsistencies is viewed as essential for the development of the biomass-to-syngas value chain. Nevertheless, the existence of already available infrastructure and syngas-to-chemicals synthesis technologies rather provides and opportunity than a barrier to the development of the biomass-to-syngas value chain

6 Step 1C & 2A: Stakeholder perceptions on value chain development

As discussed in section 3.5, the research methodology involves conducting a comprehensive exploration of stakeholders' perceptions of the value chain's development. This approach incorporates important stakeholder perspectives and narratives derived from the semi-structured interviews, facilitating the inductive formation of theories regarding the development of the biomass-to-syngas value chain and the implementation of torrefaction within it. This analysis thereby provides a descriptive examination of the current industry viewpoints on the development of the biomass-to-syngas value chain, including the significant barriers that impede its widespread adoption, as well as stakeholder solutions to overcome these barriers. The iterative analysis method used to identify and analyse these important stakeholder perspectives and narratives (see figure 9) resulted in the derivation of five main barrier and solutions themes. These main themes subsequently consist of several sub-themes which describe barriers and solutions to the development of the biomass-to-syngas value chain and torrefaction technology (see Appendices C.2 & D). In the following sections the theories regarding the development of the biomass-to-syngas value chain based on stakeholders perspectives from the analysed themes and sub-themes are further substantiated.

6.1 Market development

6.1.1 Market uncertainty

As discussed in section 5 the barriers that were added by stakeholders to the overall identified list of barriers indicated a complex and fragmented business environment. One of main insights from the stakeholder perspectives that can be aligned with this finding is the fact that most stakeholders indicated a lack of market development surrounding setting up biomass-to-syngas projects. This lack of market development can mainly be attributed to the lack of investments in the biomass-to-syngas industry caused by the highly uncertain technology market, the limited business case of biomass gasification as opposed to incumbent concurrent technologies, and the supply chain failures that exist in the value chain.
Stakeholders highlighted that the lack of investments in the industry remains a prominent barrier due to a 'wait-and-see' mentality adopted by investors and chemical firms. This investor's hesitancy can be attributed to the high investment risks associated with technical uncertainty in scaling up and commercializing the technologies [B][D][E]. Furthermore, the ongoing conflict in Ukraine has exacerbated market uncertainty and material price volatility, further intensifying this investor hesitancy [H]. Additionally, the lack of political consensus regarding the sustainability of biomass as a natural resource discourages investments in biomass-to-syngas projects among potential stakeholders out of fear for fast-evolving policy and projects lacking the political support needed to ensure profitability [C][D][F]. These barriers thereby show how stakeholders currently view the investment environment as highly risky and unsupportive to the development of the biomass-to-syngas value chain. Addressing these barriers and fostering a supportive investment environment are therefore crucial for unlocking the full potential of the value chain and driving its sustainable development. In addition to the described perspectives of stakeholders, the following quote from an industry expert captures the essence of the challenge faced by the biomass-to-syngas sector, clearly emphasising the need of creating a supportive investment environment.

> *"This is currently our greatest challenge, the barrier of convincing large companies to invest in our technology and collaborate on its development. It is the most difficult aspect we are facing, as we need to persuade them to be the first in the market to take the risk." [E]*

One of the proposed solutions by stakeholders to improve the investment environment in the industry is the development of demonstration projects , as projects aim to showcase the efficacy of the technologies, persuade investors, and gather knowledge on upscaling [B][D][F]. A commonly suggested approach is for smaller technology developers to collaborate with knowledge institutions and large chemical firms in establishing these demonstration projects. This collaboration facilitates network formation among these actors and promotes the creation of widespread knowledge about the technologies' performance, potentially reducing investor hesitancy. Stakeholder **B** specifically recommended participating in such projects through European collaborative initiatives like the Research and Innovation funding program Horizon, as it provides a broader reach to international actors and increases exposure to potential investors.
In line with this industry perspective on the importance of demonstration projects to showcase the tech-

nology's effectiveness and gain investor confidence. The following quote highlights the significance of demonstrating the scalability of torrefaction and gasification technologies to attract investments.

> *"The demonstration at a larger scale to prove that torrefaction and gasification is feasible, is essential for convincing investors." [B]*

6.1.2 Business case

The limited profitability of the biomass-to-syngas route through gasification, compared to existing or alternative technologies, has been identified as a significant obstacle to the value chain's development [E][H]. As an example, stakeholders mentioned how the competition from electrolyser technology in attracting subsidies for the production of sustainable hydrogen further hampers the business case for biomass-to-syngas projects. Stakeholders indicated how although biomass gasification can produce cheaper hydrogen compared to electrolyser technologies, the high investment uncertainty as discussed in the previous section is making electrolysis more favorable for attracting subsidies [D][E]. This inability of attracting subsidies, results in decreased cost-effectiveness and a limited business case of the projects. In addition, bio-based chemicals are currently more expensive in comparison to fossil-based chemicals [B][D][H]. This is partly caused by the lack of carbon pricing and limited subsidy support of bio-based projects in the industry, but also by the fact that the technology market for gasification and torrefaction technologies are still underdeveloped which has led to limited technology development and insufficient cost-performance of the technologies [A][F][C].

Overall, the different stakeholder perspectives show that business case of the biomass-to-syngas value chain is affected by a multitude of factors stemming from market uncertainty, policy failures and competition with incumbent or alternative technologies. Addressing these barriers will therefore require concerted efforts from policymakers, investors, and industry stakeholders to create a supportive investment climate, establish clear and favorable policies, and enhance the competitiveness and attractiveness of biomass-to-syngas technologies in the market. In this regard, stakeholders have highlighted how the business case of biomass-to-syngas can already be greatly improved by leveraging the valuable by-products generated from gasification processes, namely biogenic CO2 and biochar [D][E][H]. Stakeholder **E** specifically emphasized how the utilisation of these by-products could already compensate for the feedstock and torrefaction costs in their own business operations. This stakeholder therefore urges the value chain to focus more on trading these by-products as a means of enhancing the business case of biomass-to-syngas projects, stating that *"The mineral balance, just like the carbon balance, will be essential for the future of our value chain"*. Furthermore, the existing demand for CO2 in established conversion pathways, such as beverage and chemical production (e.g., methanol), coupled with the potential of biochar as a carbon credit product offering high-quality carbon offsets, creates favorable conditions for finding buyers for these valuable products [22][42]. Exploiting this solution proposal therefore holds promise for improving the overall business case of biomass gasification and advancing the development of the value chain [D][E][H].

Apart from the increased exploitation of by-products from the gasification process, many stakeholders view torrefaction as an essential technology to improve the overall business case of syngas production, since the technology is able to homogenise and upgrade low-value residual feedstock streams into usable feedstock streams for gasification processes [A][B][F][H]. The technology therefore allows gasification projects to make use of a wide range of low-cost feedstock and decrease the overall logistic costs on biomass supply, thereby further reducing the operational cost of syngas production and improving the business case of the overall value chain [A][C][D][E][F][G]. However, although torrefaction holds promise in lowering the logistic cost of biomass transport, some stakeholders have pointed out that the price of woody biomass is currently lower compared to torrefied pellets. This implies that the implementation of torrefaction technology could have a negative impact on the value chain's business case [A]. Nevertheless, most stakeholders emphasize the essential role of torrefaction technology in improving the business case of syngas production through gasification. The following quote illustrates this industry perspective:

> *"Ensuring the ability to utilize a wider range of biomass streams, including non-competitive sources like residual biomass and similar materials, is crucial for the advancement of economically viable gasification projects. Torrefaction can play a significant role in enabling this diversification" [F]*

6.1.3 supply chain

Figure 14: Chicken-and-egg problem long-term feedstock contracts

The development of the biomass-to-syngas value chain is greatly influenced by the supply-chain of biomass. Stakeholders describe the market for biomass trade as highly competitive and controlled by a small group of companies stemming from the paper and pulp, and chipboard industries [A]. The competitiveness of this market poses a significant challenge for biomass-to-syngas projects in securing reliable and consistent feedstock streams. The limited market power of the biomass-to-syngas sector creates a complex situation for the development and upscaling of these projects, often referred to as the "chicken and egg" problem by stakeholders, as depicted in Figure 14 [A][D][E][F][G][H]. Companies involved in biomass-to-syngas projects face difficulties in obtaining stable and long-term feedstock supply contracts due to their relatively small size in the feedstock market. These long-term contracts are crucial to attract investors for large-scale projects, as investors are reluctant to bear both the technological and supply chain risks associated with scaling up the technologies. This inability to secure feedstock contracts therefore becomes a barrier to investor participation, leading to projects remaining at a small-scale level or getting cancelled. Consequently, the situation where biomass-to-syngas projects struggle to achieve a sufficient market size to obtain long-term feedstock contracts is maintained, thereby perpetuating the vicious cycle of the "chicken and egg" problem [A][D][E][F][G][H]. As a result, SMEs are dependent on local feedstock streams and a limited market of feedstock suppliers with limited resources. The projects therefore are more prone to price volatility, since they face difficulties in addressing local shortages through international procurement [A]. According to stakeholders in the survey (E.2.1), this "chicken and egg" problem increases the challenge of investment dynamics, where dominant feedstock suppliers exploit the limited bargaining power of the SMEs and drive up their feedstock-prices independently of the quality of their feedstock production, thereby harming the business case of the biomass-to-syngas projects. Additionally, the limited market size of the SMEs prevents them from imposing the required sustainability demands on their feedstock supply [A]. Thereby further decreasing the pool of feedstock suppliers and the bargaining power of the SMEs. In this regard, the stakeholder statements below provide industry perspectives on the described barriers arising from supply chain development in biomass-to-syngas projects.

> *"In our project development setting up the supply chain was the biggest bottleneck: how do you find the right partners who can provide a sufficient and steady flow of feedstock in the long term at a competitive price and consistent quality?" [D]*
>
> *"The market for wood chips is mainly dominated by the pulp and paper industry, followed by the chipboard industry. The energy market is the smallest and primarily relies on the residual materials from these industries, making it difficult to obtain a reliable biomass stream from this source." [A]*

Although the "chicken and egg" problem poses a significant barrier to the development of a secure and economically viable supply chain for biomass-so-syngas projects, stakeholders have highlighted several possible solutions to circumvent this issue. One of these solutions is the formation of strategic partnerships between technology developers and larger companies which already operate in the biomass industry and have a stable and cost-effective biomass supply chain [A][D][F]. These larger companies can allocate a portion of their biomass supply to support the development of gasification projects. As stated by **A** *"To enter the market, small companies need to find the right partner, preferably a larger external company from the energy sector, that has access to affordable biomass. However, persuading this partner that the investment is worthwhile is crucial."* As discussed in the previous section, involving the partner in a demonstration project can help in convincing them to take on the investment risk. These partnerships would therefore allow projects to benefit from both the natural resources provided by larger companies, such as a stable and affordable biomass supply chain, as well as the financial resources necessary for project development.

Additionally, stakeholders indicated that the agricultural sector currently provides limited feedstock streams to the industry whilst there is an enormous potential from this sector to provide low-cost biomass [41]. However, a significant barrier to exert this potential is the lack of network formation between the agricultural sector and the industry [C]. To overcome this challenge, stakeholders emphasize the importance of creating financial incentives for farmers and implementing policy frameworks that promote collaboration and facilitate the formation of networks between the two sectors [A][E][F][H]. By facilitating this network formation, stakeholders believe access to affordable feedstock can be achieved, unlocking the vast opportunities offered by the agricultural sector in supporting biomass-to-syngas projects.

Furthermore, the participants highlighted the implementation of torrefaction technology in the value chain as a route which can help in improving the supply chain of biomass to the industry. Apart from the notion that the technology can improve the logistics of certain feedstock streams in the supply chain [A][C][D][E][F][G], experts emphasize its role in diversifying the range of usable feedstocks for gasification is essential for the successful development of the value chain [F][H]. This further becomes clear from expert **H**'s statement, stating that *"torrefaction is essential for upgrading low value feedstock streams in order to increase the reach of usable raw materials."* Since, by increasing the reach of usable feedstocks for syngas production, the security of supply of gasification projects can be increased and the dependency on a small group of suppliers is minimized.

Additionally, stakeholders have emphasized another critical role for torrefaction technology, namely the conversion of a diverse range of feedstocks into homogeneous and tradable commodities [C][D]. Many of the experts think that the existing biomass streams are too diverse in their quality and characteristics to facilitate mass trade and transportation [A][C][D][E][F]. Therefore, torrefaction is expected to become crucial in homogenizing diverse biomass streams into consistent, high-quality commodities. This step is considered vital for advancing the value chain's development, as becomes clear from the following expert quote:

> *"I firmly believe that torrefaction plays a essential role in optimizing and upgrading biomass streams, in order to obtain marketable commodities with a quality assurance label, enabling smooth trading. Considering the immense volumes of biomass that need to be transported, torrefaction will become a crucial process." [C]*

By emphasizing the ability of torrefaction to standardize biomass and create marketable products, stakeholders underscore its significance in driving the value chain's expansion and facilitating efficient trade and transportation.

6.2 Policy and subsidy

6.2.1 Public debate

As mentioned in subsection 6.1 stakeholders have highlighted the role of political uncertainty in hindering the progress of the biomass-to-syngas sector. The ongoing public debate and lack of political consensus surrounding the sustainability of biomass as a natural resource and its contribution to a future sustainable economy have thereby been identified as major factors impeding policy formation in this sector [A][B][C][D][F][H]. This absence of clear policy frameworks has significantly complicated the allocation of subsidies to bio-based projects and thereby hampered the development of the value chain [D][F] . Moreover, stakeholders perceive this public debate regarding the sustainability of biomass usage as lacking scientific validity or credibility, primarily stemming from a lack of widespread knowledge on sustainable biomass utilization. Additionally, stakeholders frequently expressed their concerns regarding the broad categorisation of the term 'biomass' which provides sufficient differentiation between various biomass streams. Stakeholders feel that this broad generalization, combined with the negative perception associated with biomass, further increases the polarization in the public debate and impedes the formation of effective policies [A][B][D][E][F]. The public debate therefore heavily affects policy and subsidy formation regarding the development of the value chain. The following composed quote from the stakeholder process further underlines these findings.

> *"The public debate surrounding biomass poses a significant challenge. Moreover, the broad categorization and negative externalities associated with the term 'biomass' hinder policy and subsidy formation [B][F]. It is therefore crucial to establish consensus on the essential role of biomass in achieving sustainability across multiple carbon-intensive sectors [C]."*

Additionally, stakeholders pointed out that although they support sustainability goals in general, they feel that the political environment and subsequent policy formation has an excessive amount of focus on ensuring sustainability. This excessive focus on sustainability has stifled the development of the value chain rather than supporting it, according to the stakeholders [A][C][E][H]. This view on current sustainability criteria by the industry can clearly be depicted from the interview quote below.

> *"A major bottleneck is that the discussion predominantly revolves around sustainability, which is undoubtedly crucial. However, the excessive focus on sustainability and its regulation consumes disproportionate attention, leaving the development of value chains with insufficient policy attention [C]."*

6.2.2 Effectiveness of policy and subsidy

The lack of policy and subsidy schemes that promote the development of the biomass-to-syngas value chain is a direct consequence of the polarized public debate and excessive focus on sustainability in the political realm. One prominent concern raised by stakeholders is the mismatch between existing subsidy schemes and the specific needs of value chain development in the biomass-to-syngas sector [C][D][E]. The current sustainable subsidy schemes primarily target either the further advancement of technologies to higher TRL-levels through supporting the development of small-scale pilot plants or the financial support of operational expenses for already commercialized sustainable technologies. However, these schemes overlook the crucial phase of scaling up gasification and torrefaction projects to a commercial level, as the requirements for upscaling the technologies are not based on either the further advancement of the technologies' TRL-level or the support of operational expenses. Instead, stakeholders indicate that the focus should be on attracting investors to invest in commercial-scale projects and addressing the short-term risks associated with the high capital investments that come with the development of such a commercial-scale project. Therefore, there is a need for subsidies that specifically target stimulating commercialization of the technologies and the provision of incentives for investors to contribute to the development of the biomass-to-syngas value chain [C][D][E]. The interview quote below effectively shows how industry stakeholders perceive current subsidy schemes.

> *"A major obstacle in our industry is the mismatch between the subsidy schemes and what is needed to cover the risk. Current subsidies do not have the desired effect, and there is a lack of short-term support to mitigate investment risks and attract investors." [E]*

In addition to the mismatch between subsidy schemes and the specific needs for value chain development, current subsidy schemes do not aim at stimulating the production of bio-based syngas. Some stakeholders believe this is a result of the negative public debate or competition with alternative technologies, while others believe the value addition of syngas is challenging to measure since it resembles a semi-finished product [D][G]. Either way, this absence of subsidy aimed at the production of bio-based syngas once again shows that the chemical sector is underexposed in current policy and subsidy schemes, thereby further hampering the development of the value chain. As can be derived from the quote below, stakeholders perceive this issue as disruptive to the development of the value chain.

> *"When you look at the Netherlands, there are subsidies available, but they are mainly focused on green hydrogen from electrolysis. That's why it seems that in the new subsidies like SDE++, DEI+, and national green capacity, the biogenic/biomass component is missing. Specifically, biogenic hydrogen is overlooked or excluded, and this is disruptive to the project development."[D]*

As a solution to these problems, experts have proposed the development of subsidy schemes or risk-funds specifically designed to provide financial support and mitigate the investment risks associated with commercializing gasification projects [D][E][H][E.2.4]. Although such active governmental investment opportunities such as InvestNL already exist, experts argue that these initiatives are too limited in scope and slow in implementation to effectively meet the needs of the industry. Therefore, the industry experts that were interviewed strongly support the development of a bio-based project-specific risk-fund, which would provide timely and sufficient support to the sector, as is evident from the following interview quote.

> *"So I don't think that more subsidies are the solution, but rather a risk fund that provides incentives and a sort of industrial policy where the industry has the perception that if things go wrong, the risks are covered, and otherwise, I have a very solid business case. So I think that could be a solution, and there are parties that do this, but they are small, like Invest NL. So in that sense, it just takes too long for appropriate support to be available." [E]*

6.2.2.1 Dynamic policy landscape and path dependency

Another barrier emphasized by stakeholders are the challenges posed by the dynamic European and national policy landscape on sustainability and climate. The rapidly changing and complex policies hinder industry stakeholders, including chemical firms, from making long-term strategic decisions regarding the adoption of bio-based technologies, thereby slowing down the progress of sustainable biomass-to-syngas projects [B][C][H]. Moreover, stakeholders highlight the path dependency of industry and politics as a barrier to transitioning to sustainable bio-based technologies, as the lack of specific policies addressing the carbon footprint of the chemical industry undermines companies' motivation to prioritize sustainable initiatives and therefore impedes the transition towards a more sustainable industry [B][C][D][H]. Additionally, the prevailing market structure which is focused on short-term profits and dividend payments, was identified as a broader societal issue rather than a challenge specific to the biomass-to-syngas value chain [B][E]. Nevertheless this barrier is still contributing to the path dependency of carbon-based industries and thereby impedes the industry stakeholders' efforts to embrace sustainable technologies. An example which was often given by stakeholders is the heavy lobby of carbon-based industries against certain climate policies and technologies, as is shown in the quote below.

> *"I can imagine that the lobby from these industries is very strong as they are highly competitive sectors, mainly focused on exports. So I can understand that these companies would heavily lobby against levies that could negatively impact their market position, potentially leading them to relocate from the Netherlands." [C]*

6.3 Law and regulation

As discussed in the previous section, stakeholders perceive the political environment as having a singular emphasis on sustainability in policy making. As a result, stakeholders express there is an excess of regulations and certifications flooding the market, making the value chain more complex to build [A][B][C][G][H]. One of the challenges arising from the overwhelming number of regulations and certifications is the difficulty of complying with sustainability regulations due to variations in regulations and certifications across countries, which negatively impacts the tradability of biomass [A]. In addition some stakeholder feel like the abundance of certifications disproportionately increase the transaction costs on the use of bio-based resources compared to fossil based resources [C].

Furthermore, stakeholders indicated that the current permitting schemes, particularly the ones surrounding the political debate regarding nitrogen deposition in the Netherlands, significantly affect the establishment of the value chain. Current permitting schemes are found to be too complex and lengthy for the development of the value chain, as they can pose a threat to the survival of SMEs involved in biomass-to-syngas projects, since SMEs lack the financial resources to handle high administrative costs and prolonged permit procedures [C][D][G][H]. Moreover stakeholders expressed their concerns that the ongoing debate and uncertainty surrounding nitrogen deposition and building permits is deterring investors to invest in projects in the Netherlands, driving them off to invest in projects abroad. Overall, current permit processes are seen as too complex and sluggish, posing a significant barrier to the development of the value chain (see quote underneath). An expert solution proposal was therefore to advocate the development of separate permit procedures for green initiatives that circumvent the nitrogen deposition issue in the Netherlands [E.2.4].

> *"The permit processes, in particular, are complicated, slow, and uncertain. The permit processes need to be improved and simplified, but in the Netherlands, they are too complex. Europe, and especially the Netherlands, are very good at discussions and reaching consensus, but as a result, we are too slow. Permit procedures and public consultation processes are so complex and lengthy that by the time you can start construction, you are already lagging behind the facts" [H]*

Additionally, stakeholders have indicated that there is a lack of enforced measures to discourage the use of fossil fuels in the chemical sector. Stakeholder **H** specifically mentioned that this lack of enforced measures deterred his company from pursuing developing gasification projects for the chemical industry, as it prevents making a proper valuation of prices and projects, unlike in other industries. A frequently mentioned example of industries where specific laws and policies act as a driver rather than a barrier, is the biofuels sector. Stakeholders **E**, **G**, and **H**, which are technology developers, all indicated that the recent EU-wide FitFor55 policy, in which admixture obligations were announced, sparked a significant drive to invest and develop in this sector and led to increased business opportunities for their companies. Although the chemical sector is indirectly affected by the FitForr55 policy through the introduction of an EU emissions trading system (EU-TS) and Carbon border Adjustment Mechanism (CBAM), no sector specific regulation is included in the policy-scheme [19]. As can be derived from the following stakeholders' description of the impact of the FitFor55 measures on his business, the lack of enforced measures aimed at the sustainable transformation of the chemical industry can hence be seen as a missed opportunity to the development of the biomass-to-syngas-to-chemicals value chain. Efforts should therefore be made to include uniform regulation specified towards the sustainable transition of the chemical sector and discourage the use of fossil-based resources [A][B][F].

> *"The past six months have been a whirlwind for our company, with obligations such as blending requirements for green gas in urban areas and fuel obligations and blending requirements for SAF in airplanes. Currently, there is a high demand for e-fuels in Germany, and our phones have been ringing off the hook. The entire market needs DME, for instance, to blend into this fuel, and ultimately, there will be a demand for 100% blending. Thus, the industry is truly experiencing a noticeable drive towards sustainability." [E]*

6.4 Technological failures

Although there was a general consensus amongst interviewees that the barriers to the development of the biomass-to-syngas value chain stemming from technological issues are surmountable, they also highlighted several significant technological issues that could hinder its progress. One major issue which was frequently mentioned is the high technological and commercial uncertainty surrounding the scalability of both technologies [B][C][D][E][F]. Since, both technologies are still of low technological maturity with an estimated TRL level between 7-8, and there are no examples of operational commercial scale plants which have presented a profitable business case thus far there are uncertainties regarding the upscaling of the technologies. This technological uncertainty, combined with the high investment cost for commercial scale torrefaction- or gasification plants, are therefore discouraging investors from supporting such projects [B][D][E][F]. Stakeholders emphasized that technology developers must first showcase the performance of their technologies on a small scale in order to attract financing for commercial-scale projects. Therefore the development of demo-plants once more presents a solution to the growth of the value chain by showcasing technological performance and generating essential knowledge regarding upscaling of the technologies [B][D][F]. The following interview quotes underscore the perceived importance of demonstrating technological viability to potential investors.

> *"We definitely observe a growing interest from companies and industry organizations now that we have demonstration projects that provide evidence of the technology's effectiveness."[B]*
> *"The pilot plant plays a vital role in establishing our credibility by showcasing our ability to produce customized products from diverse biomass streams. It effectively mitigates investment risks and provides tangible evidence of our technological readiness, thereby reducing uncertainties."[F]*

Apart from the technological uncertainties regarding the scalability of both technologies, industry experts described that both technologies also suffer operational issues and a limited flexibility of processing varying feedstock streams. In fact, stakeholders indicated that the *"heterogeneity of feedstock causes uncertainties in the development of gasification projects"*[H] as gasifiers have a limited flexibility of obtaining high quality syngas out of differing feedstock streams. Similarly, for torrefaction, it was noted that *"not all biomass streams can be handled in the same reactor"*[F]. Additionally, the uncertainty in project development is further increased by the existence of several different reactors, each with its own limitations on compatible feedstock streams it can process. Technology developers currently deal with this problem by limiting the use of varying feedstock sources in their projects. This however further increases the dependency on a limited amount of feedstock suppliers and thereby the investment dynamics problem as discussed in section 6.1.3 on supply chain challenges.
Both technologies also encounter operational challenges that hinder their progression to commercial scale. These challenges primarily arise from the composition of biomass feedstock and their reaction characteristics within the thermo-chemical processes. Stakeholders highlighted the issue of tar and slack formation in gasification [E]. Similarly, torrefaction faces technical difficulties related to tar and ash formation, as well as limited pelletization of torrified biomass after the torrefaction process [B][F]. While these issues can significantly impact the operational performance of both technologies, the technology developers emphasized in their interviews that these issues are preventable through comprehensive testing and a meticulous installation setup. Moreover, the implementation of torrefaction in the value chain can improve the gasification characteristics of feedstock and with that allows for better reaction kinetics and cleaner syngas yields according to experts [D] & [E]. Additionally, two of the interviewees [E][F], mentioned incorporating a modular design of reactors can circumvent lack of knowledge and issues regarding upscaling. Although these solutions do not effectively solve the operational issues of the technologies, they could facilitate the development of the first commercial scale projects which would allow for the development of the value chain and increased business opportunities.
Perhaps an even more significant issue in the development of these technologies is the limited network formation between knowledge institutions and chemical firms. According to stakeholder **B**, companies are unwilling to disclose information regarding the chemical substances required for their operational processes due to concerns of potential leaks to competitors. This lack of transparency from chemical firms towards knowledge institutions hinders efficient research and development and leads to processes that do not align optimally with their operations, resulting in a slower adoption of gasification and torrefaction technologies. Furthermore, the shortage of skilled professionals in the labor market was mentioned as another factor slowing down R&D and engineering processes [F]. Overall, stakeholders describe a situation

in which there is a lack of widespread technological knowledge regarding the technologies, particularly when it comes to understanding the commercial applications of the technologies [E]. The successful development of these technologies into commercially viable processes is therefore not solely dependent on attracting external financing, but also relies heavily on the willingness of chemical companies to engage in open collaboration for research and development activities, as well as the industry's ability to attract a sufficient number of skilled professionals. To improve the development of the value chain, stakeholders should therefore strive to actively pursue enhanced network formation within the industry between the business sector and knowledge institutions, and enhance the diffusion of both technological and commercial knowledge concerning the technologies amongst industry actors [B][D].

7 Step 2A-B: Barrier prioritisation & solution development

7.1 Barrier prioritisation

To address the third and fourth research sub-questions, a prioritization of thirteen barriers was established based on stakeholder input, specified in table 7 below. This prioritization was derived from the most frequently mentioned barriers identified during the pre-assessment phase of this research from Table 9. Additionally, stakeholders who were unable to participate in the webinars or interviews provided their input through a questionnaire (see Table 20), further contributing to the identification of key barriers. These barriers were categorized based on the themes derived from stakeholder conversations and thematic analysis. Additionally the TIS-building block and influencing condition are specified to create an understanding of the most pressing building block-failures which hamper the development of the value chain

#	Barrier	Type of barriers (TIS & Influencing condition)
	Policy	
1	There is high political uncertainty surrounding the use of biomass due to a strongly polarised public debate combined with issues surrounding the nitrogen deposition crisis. Result in limited policy attention regarding the development of biomass-to-syngas technologies	Network formation and coordination & Socio-cultural aspects
2	There is a lack of both EU and NL long-term policy specifically aimed at making the chemical sector more sustainable	Innovation specific institutions & macro-economic and strategic aspects
3	Fast changing climate policies and political uncertainty, lead to a lack of investments in the industry	Network formation and coordination & Socio-cultural aspects
	Subsidy	
4	Subsidies do not properly cover the investment risks of gasification projects and do not support the development of commercial large-scale projects.	Innovation specific institutions & Natural, human and financial resources
5	Due to low policy attention there are no subsidy schemes that focus on bio-genic syngas production	Innovation specific institutions & macro-economic and strategic aspects
	Law and regulation	
6	Complicated and slow permitting schemes slow down projects and form administrative and financial barriers to SME technology providers, and a hindrance to attracting investors	Innovation specific institutions & Natural, human and financial resources
7	Lack of carbon pricing of the chemical industry results in a lack of motivation for companies in the sector to prioritize sustainability initiatives, and a unfair competitive advantage of fossil-based chemicals over bio-based chemicals	Innovation specific institutions & macro-economic and strategic aspects
8	The term 'biomass' is too broad and does not distinguish between (sustainable) different biomass-feedstock streams. Additionally countries have highly varying certification schemes for determining the sustainability of biomass, resulting in limited tradability of feedstock.	Innovation specific institutions & Lack of knowledge and awareness of application and market
	Market formation	
9	The high investment costs combined with high technological risk make investors hesitant to invest in biomass-to-syngas projects, resulting in limited investments in the industry	Production system & Natural, human and financial resources
10	Chicken and egg problem: technology providers struggle to secure long-term feedstock contracts due to their limited market share, making it difficult to attract external investors. Consequently, the lack of investments hinders company growth, perpetuating a vicious cycle of companies unable to expand or obtain sustainable feedstock contracts.	Network formation and coordination & Natural, human and financial resources
11	Limited ability to secure reliable feedstock supply of consistent quality due to limited availability and heterogeneity of the feedstock	Product performance and quality & Natural, human and financial resources
	Technological	
12	Limited flexibility of gasification technology to handle diverse feedstock, limiting project to specific types and ratios, resulting in reliance on suppliers and hindered adaptability to supply chain fluctuations or uncertainties.	Production system & Knowledge and awareness of technology
	Entire value chain	
13	There is lack of awareness and non-uniformity of knowledge base regarding gasification technology among industry, institutions, local bodies, consumers, and entrepreneurs hindering the further exploitation of biomass applications ultimately leading to market failures	Production system & Knowledge and awareness of technology

Table 7: Prioritisation barriers to value chain development

As can be derived from the prioritization in Table 7, stakeholders primarily emphasized barriers associated with failures in the building blocks of innovation-specific institutions, network formation and coordination, and production system within the TIS of the biomass-to-syngas value chain. Furthermore, the distribution of the influencing conditions was found to be more widely spread. These findings align with the conclusions drawn in subsection 5.1, where a similar pattern emerged from the comprehensive list of barriers. This finding thereby further highlights that the solution space mainly evolves around these three building blocks and solutions should address multiple influencing conditions to rectify the deficiencies in a building block.
Additionally, previous sections have demonstrated the interconnected and interactive nature of barriers, whereby failures in one TIS building block can trigger subsequent failures in other building blocks. This finding can also be derived from the list of prioritised barriers above, for example, we can observe that the barrier of high political uncertainty (#1) can cause a failure in network formation and coordination by deterring investors from the industry due to creating high market uncertainty (#3). Moreover, the lack of adequate or completely absent subsidy schemes for gasification projects and the production of biogenic syngas (#4 & #5) can partly be attributed to the lack of policy attention and long-term sector specific policy (#1 & #2). This interactiveness and connectiveness of barriers imply that a single solution should encompass multiple aspects and has the potential to address multiple barriers. This finding aligns with the research of van Bruggen et al., which found that interconnected barriers require a mix or synergy of different types of solutions and a systemic approach to overcome them [62]. Therefore during the solution development phase, which is included in section 8 of this research, barriers were grouped according to their correspondence and ability to be solved by and all-encompassing multidisciplinary solution.

7.1.1 Prioritisation of barriers to the implementation of torrefaction technology

Using a similar method to the one discussed in the previous section, stakeholders were asked to prioritise the barriers which hampered the implementation of torrefaction technology into the value chain. This resulted in the following list of prioritised barriers in table 8 below. As is clear from this overview, stakeholders perceive the main limiting factor in the implementation of torrefaction technology in the value chain the performance of the technology itself caused by a lack of fundamental and applied knowledge and awareness of the technology. Thereby indicating that the fundamentals of the technology are being poorly understood by both industry stakeholders as well as knowledge institutions. Such low performance and immaturity of the technology can impede the development of the biomass-to-syngas value chain, as torrefaction serves as an enabling technology for improving the logistics and gasification process performance within the value chain [55]. Therefore, these findings emphasize the need for intensified efforts to enhance fundamental knowledge concerning the performance and development of torrefaction technology.

#	Barrier	Type of barriers (TIS & Influencing condition)
1	Process interruptions occur frequently due to technical challenges in achieving constant and well-controlled process conditions for the production of a uniform product	Production system & Knowledge and awareness of technology
2	Low technological maturity and the lack of knowledge regarding upscaling the technology	Production system & Knowledge and awareness of technology
3	The content of inorganic compounds in ash increases during torrefaction, which limits the utilization of torrefied biomass in gasification and combustion practices	Production system & Knowledge and awareness of technology
4	Limited flexibility of torrefaction technology to process biomass with varying properties in the same reactor type	Production system & Knowledge and awareness of technology

Table 8: Prioritisation barriers torrefaction technology development and implementation

In addition to the barriers related to the technological performance of torrefaction, the interview process brought up a significant point of discussion regarding the implementation of torrefaction technology in the value chain. Specifically, stakeholders debated whether the technology should be decentralized, located near the feedstock source, or centralized at the gasification plant in the Netherlands. While integrating torrefaction into a centralized and fully integrated biorefinery will omit the benefits of torrefaction to the supply chain, some stakeholders expressed concerns about a potential principal-agent problem if

torrefaction is implemented decentrally near the feedstock source. Stakeholder **[A]** emphasised that by constructing a large-scale torrefaction plant at the biomass producer's location, a the significant amount of power is granted to the biomass supplier in such a scenario. Stakeholders therefore worry that the biomass supplier could exploit this power to increase the feedstock price, since the torrefaction asset holder is reliant on a steady supply and cannot easily switch to alternative sources [D]. The investment made by the asset holder in the torrefaction plant therefore creates a situation where the feedstock producer can exploit their position and exert pressure on the asset holder.
Other stakeholders have disputed this viewpoint by emphasising that torrefaction technology has to be implemented decentralised near the feedstock source in order to provide optimal value addition to the value chain. However, these stakeholders also acknowledge the potential of a principal agent problem and therefore propose the development of small scale decentralized hubs which are customised according to the location of feedstock production [B][C][F]. By making small scale customised torrefaction hubs the dependency on a single feedstock supplier in the region is reduced and since the unit-size of the plant is customised to the production location, the capital expenses per plant are limited compared to a single large-scale plant. However, stakeholder **[F]** notes that this approach results in a complex logistical business case, requiring numerous contracts and certifications to be managed simultaneously. Therefore the stakeholders emphasise that the supply chain can be structured in a hybrid manner, with some parts decentralized and others centralized, depending on the availability of feedstock in a region and the level of dependence of the torrefaction plant on one or several feedstock suppliers [E][F]. This viewpoint aligns with literature, where Thengane et al. and Kang et al. suggest that regions with abundant biomass should prefer centralized large-scale designs, while regions with limited biomass and a seasonal dependence should favor decentralized small scale designs [61][29]. A representation of such a hybrid structured supply chain is shown in Figure 15 below, in which Wild et al. describe a feedstock supply system design concept that incorporates distributed and location specific torrefaction hubs as pre-processing depots in combination with centralized terminals. Furthermore, by taking various biomass resource types and pre-processing them through torrefaction into products that are dense, aerobically stable, and capable of being managed in existing material handling infrastructures, the hybrid supply chain setup enables the production of economically viable commodities [67].
Additionally during the expert reflection session (see appendix F), experts also acknowledged the complexity of the logistical business case associated with the utilization of low-value feedstock streams from decentralised torrefaction units. Nevertheless, the experts unanimously agreed that torrefaction should be developed decentralised and customised to according the to the location of feedstock production (see paragraph F.2.1.5). Thereby emphasizing the importance of the technology in producing homogeneous and tradable commodities for the value chain. Furthermore the unanimity of experts regarding decentralisation, shows that the complex logistics is perceived to be surmountable and not a substantial hindrance to the development of the value chain.

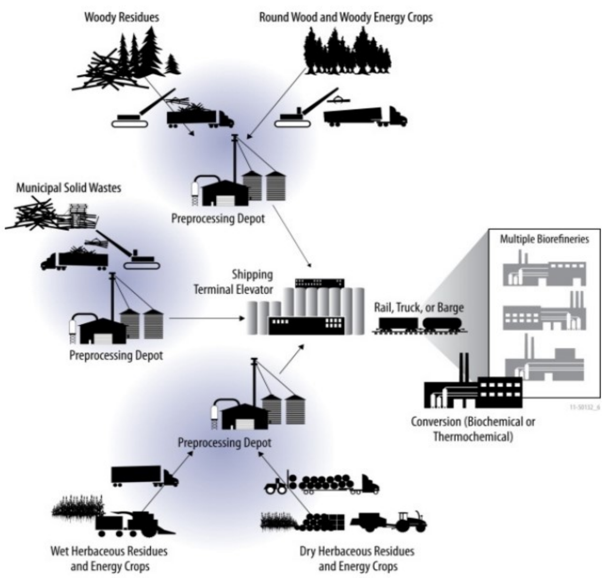

Figure 15: Decentralised supply chain set-up [67]

8 Step 2C: Developing solutions with the chain through expert reflection

In this section the sub-questions: What potential solutions can be derived from stakeholders to address the prioritized barriers in the biomass-to-syngas value chain?, How do experts assess the barriers and solutions, derived from stakeholders' perspectives, for the development of the biomass-to-syngas value chain?, and How do experts evaluate the implementation and role of torrefaction technology in the value chain? are addressed.

To address these sub-questions, a webinar was organized to facilitate an expert reflection session and conduct live polling among industry stakeholders, as described in section 3.4.3. As demonstrated in previous sections regarding the analysis and prioritisation of barriers, barriers are connected and interact. Therefore, addressing the identified barriers requires a comprehensive solution that incorporates various approaches, including economic, legal, and organizational incentives, in order to achieve optimal effectiveness [62]. Hence, the webinar was designed in such a way that the most pressing (see Table 7) and interconnected barriers were presented together, and a solution proposal was formulated which aimed to offer a comprehensive approach to address these barriers. This approach allowed experts and industry stakeholders to respond to barriers, evaluate the feasibility of the solutions, provide nuanced insights into the proposed solution areas, and even propose additional solution areas. The transcript and analysis from this webinar can be found in Appendix F and will serve as input to this solution analysis together with the data derived from stakeholder interviews and questionnaire in appendix C.2 and E.

The figures 16 to 20 below, depict the solutions derived from literature, questionnaire input and stakeholders to the prioritised and interconnected barriers which block the development of the biomass-to-chemicals value chain through gasification. The green box represents nuanced or additional solutions discussed during the expert discussions, while the grey box represents the comprehensive solution statement that served as input for the discussions. Additionally, the graph represents the outcome of the live polling of industry perspectives on the feasibility of the solution statement.

The solutions are presented in the order of how industry stakeholders rated their feasibility and importance in driving the development of the value chain. As can be derived from the figures, the proposed solutions mainly deal with the development of innovation specific institutions, network formation and coordination and development of the production system. This aligns with the findings of the building block analysis and the prioritized barriers presented sections 5.1 and 7. Stakeholders therefore anticipate that solutions emphasizing policy measures and economic incentives, such as the development of uniform policies and regulations, implementation of international standards, and offering government-driven investment opportunities and subsidies, will have the most significant impact. Conversely, solution proposals which predominantly focus on network formation and collaboration throughout the value chain, as well as research and development initiatives aimed to enhance knowledge and awareness of the technologies were rated lower in terms of feasibility.

Experts support the industry perspective that financial and policy drivers are crucial for advancing the biomass-to-syngas-to-chemicals value chain. They emphasize that the main barriers to the sector's sustainable transition are not stemming from technological challenges but from economical problems, where fossil-based resources remain more cost-effective than bio-based alternatives. Therefore, experts stress the importance of implementing measures such as carbon pricing to bridge the cost gap between fossil and bio-based resources, as gasification projects will struggle to succeed without these initiatives. Furthermore, experts argue that gasification projects should be developed on a commercial scale rather than small-scale demonstration plants to improve project profitability.

Having presented a general overview of the proposed solutions and industry stakeholders' perspectives, the following sections will delve deeper into the individual themes and solutions, providing a detailed analysis of their feasibility, potential challenges, and implications for driving the development of the biomass-to-chemicals value chain through gasification.

8.1 Solution I: Industry tailored subsidy

Based on figure 16 presented below, there can be derived that stakeholders have prioritized three barriers related to the inadequate or absent subsidies for supporting bio-genic syngas production and large-scale gasification projects. This insufficient availability of financial support has resulted in uncovered high investment risks, thereby impeding investments in the industry and limiting the development of the value chain. To address this issue, several solutions have been proposed, including modifications to existing subsidy schemes and the introduction of bio-based specific subsidies. Among these solutions, the most commonly mentioned approach involves the establishment of a risk fund or subsidy that combines support for both capital expenditures (CAPEX) and operational expenditures (OPEX). This solution aims to mitigate the short-term risk associated with substantial capital investments and cover the operational costs during the initial phase of operation.The proposed solution statement, aiming to enhance accessibility of governmental active investment opportunities for the bio-based chemistry sector, therefore received widespread support from both industry stakeholders and experts. However, experts added that although there currently already exist active investment programs of the government (InvestNL), they are too slow and complex to provide the necessary support the industry needs. Additionally, the experts highlighted the importance of fitting subsidy schemes as a solution to the "chicken and egg" problem which was discussed in section 6.1.3. They emphasized that without sufficient financial support from the government, the development of commercial-scale gasification projects will be hindered, leading to supply chain failures and impeding the progress of the value chain. Overall, stakeholders and experts are in agreement that customized subsidy schemes should be developed to offer sufficient and timely support that is needed for the development of the value chain.

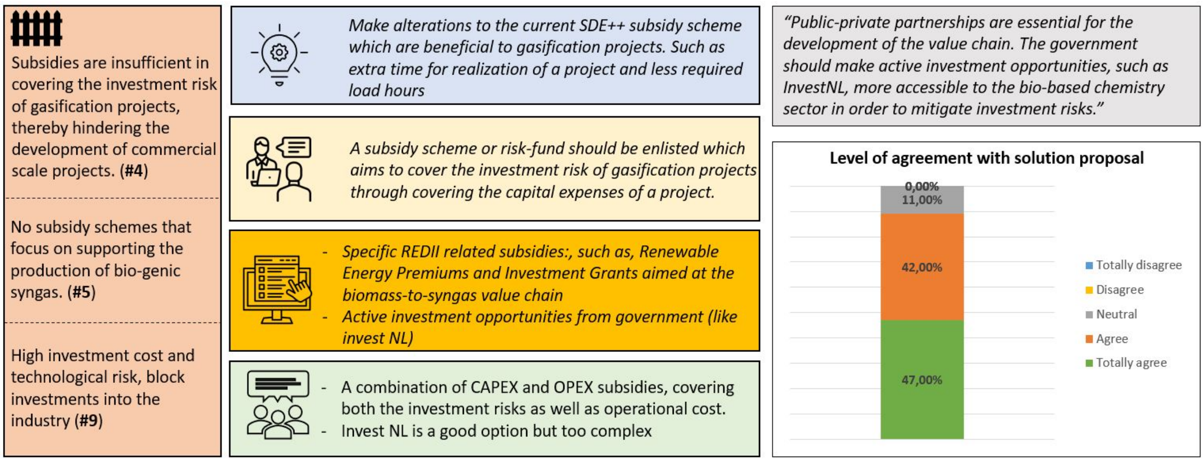

Figure 16: **Solution I:** Public-private partnerships through governmental investment opportunities [38]
Legend: | **Gate icon**: Barrier(s) to which the solution is presented; | **Lamp icon**: Solution derived from literature; | **Interview icon:** Solution derived from stakeholder interviews; | **Survey icon:** Additional or alternative solutions from stakeholders; | **Discussion icon:** Nuance provided through expert discussion

8.2 Solution II: Cohesive policy on EU-level

Based on the information presented in Figure 17, it is evident that four interconnected barriers can be identified. These barriers are linked to failures in policy formation due to a lack of network formation and knowledge and awareness of gasification technologies. The solutions stemming from literature and stakeholder interviews therefore indicate that the barriers can best be overcome by creating cohesive and EU-wide policy regarding sustainable biomass specifically aimed at the chemical industry.
The level of agreement with the solution proposal shows that industry stakeholders by enlarge agree with this solution statement and advocate the development of more cohesive policy formation. Stakeholders emphasize that the development of cohesive policy should not be limited to a national level but should be addressed at the European Union (EU) level. This necessitates collaboration across the entire value chain among policymakers, industry, and academia to achieve political consensus on the use of biomass as a sustainable raw material. Moreover, due to the global nature of the bio-based chemical industry, the design of solutions must take into account its international scope. Therefore, many regulations that impact stakeholders in the Netherlands are determined at the European level, so implementing solutions on a European scale will enable a more comprehensive and coordinated approach to driving the transition from a systems perspective [62].

Experts unanimously agree on the necessity of cohesive policy schemes specifically aimed at enhancing the sustainability of the chemical sector. They emphasize the importance of policymakers consistently having a clear stance on sustainable biomass usage. However, the experts nuance the statement that focus should be on creating widespread knowledge regarding gasification technology, deeming it as a too complicated subject to convey to the general public. They therefore propose the focus should be on convincing the general public of the sustainability potentials of biomass and that by using biomass the building blocks of chemistry can be synthesized scalable and sustainable.
Nevertheless, some stakeholders have expressed concerns regarding a potential drawback of the proposed solution outlined in figure 17. Specifically, they believe that the complexity of the suggested "triple helix" approach might be perceived as excessively lengthy and intricate, and argue that involving only engineers could lead to a more efficient development of the value chain. In this regard, the governmental expert acknowledges that policy formation has been sluggish, and even now, there is ambiguity concerning the role of biomass in government policy. However, the expert highlights that the lack of market development can also be attributed to the continued cost advantage of fossil-based chemicals over bio-based alternatives. This indicates that addressing sustainability challenges in the chemical sector requires not only cohesive policy frameworks and stakeholder collaboration across the value chain but also internalizing the negative external effects of production methods into product prices. Moreover efforts should be made to enhance the general public image of biomass as a sustainable resource.

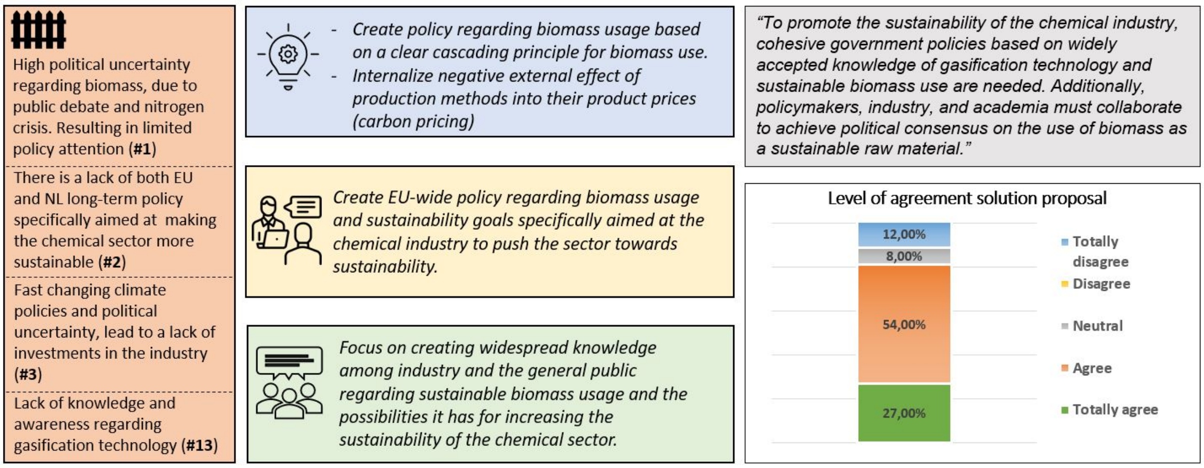

Figure 17: **Solution II:** Eu wide uniform policy formation & Development of widespread knowledge and awareness of biomass sustainability [56]

8.3 Solution III: Uniformity of regulations and certifications

As can be derived from figure 18 below, two barriers regarding failures in law and regulations can be identified and grouped. These barriers highlight that current permitting schemes are found to be slow and complicated resulting in administrative and financial barriers to technology providers in attracting investments administrative and financial barriers to technology providers in attracting investments. Additionally current certification schemes are highly varying, impeding the tradability of biomass feedstock. To address these challenges, the proposed solution advocates for the implementation of uniform European laws and regulations, as well as an international standard for sustainable biomass. This approach aims to enhance the tradability of biomass, increase marketability, and simplify the establishment of sustainable biomass-to-syngas value chains.
Industry stakeholders largely support the solution statement and advocate the development of EU-wide uniform law- and regulation and an international standard regarding sustainable biomass usage. However, they did highlight that in the revised EU Renewable Energy Directive (REDIII), voluntary schemes and national certification schemes of EU countries have to be recognised and approved by the European Commission [45]. This recognition therefore already ensures more uniformity among certification schemes and improves the tradability of biomass feedstock among member states.
Nevertheless, the experts did agree that law- and regulation and standardisation should be made more uniform on a European level to enhance the tradability of biomass feedstock. Although they did not necessarily believe there is an excess of regulations and certification on biomass, they did highlight that the market of biomass is much stricter regulated compared to fossil fuels and suggest this should be

equalised to establish a level playing field. Additionally, the experts emphasized the importance of feedstock commoditization for enhancing the tradability of biomass and fostering the development of the value chain. They stress that in addition to uniform regulations, creating a market for standardized and homogeneous feedstock is crucial in circumventing the complexities associated with handling various types of biomass. Therefore, the industry expert proposed the industry should shift towards the utilization of torrefied material in order to enable the use of diverse feedstock streams and enable the tradability of a homogeneous feedstock. Although stakeholders commented positively on this expert proposal, they did provide a sceptical note by highlighting torrefaction technology has never been successfully developed on commercial scale, thereby adhering to the barriers regarding technological uncertainty of the technology. Nevertheless, the need for commoditisation highlights the potential role and impact of torrefaction technology in the value chain.

Furthermore, experts and stakeholders once again stressed the importance of convincing the general public and politicians about the necessity of a sustainable carbon source for the production of sustainable chemicals, biofuels, and other products. They emphasized that biomass plays a crucial role in providing this sustainable carbon. Therefore more efforts should be put in enhancing knowledge and awareness of biomass technologies, their applications, and markets among policymakers, industry professionals, and academia. These endeavors are essential for achieving political consensus on the utilization of biomass as a sustainable raw material.

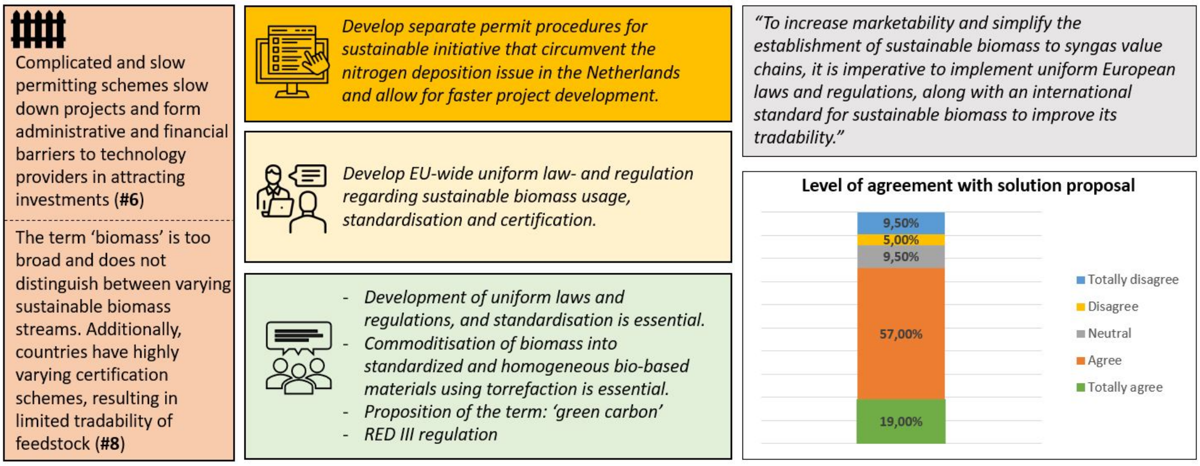

Figure 18: **Solution III:** EU-wide uniform law and regulation and standard on biomass

8.4 Solution IV: Enhance network formation and diversity of feedstock supply

From figure 19 there can be derived that the main barriers to market formation in the value chain are stemming from technological uncertainties and supply chain issues. However, as was mentioned in section 6.4, stakeholders perceive barriers pertaining to technological issues as surmountable. Experts support this perspective and emphasize that an economical barrier exists where fossil resources are relatively cheaper than biomass and its conditioning into chemicals. Consequently, the majority of solution proposals from stemming from interviews and the webinar focus on improving the business case of gasification projects, attracting external investments, and enhancing network formation with feedstock suppliers to diversify and ensure a stable supply.

While the solution proposal from the webinar recommended investing in pilot plants to enhance knowledge of torrefaction and gasification technology and securing strategic partnerships with players from the energy sector to ensure long-term feedstock contracts and a reliable supply, industry stakeholders expressed differing opinions on the feasibility of this approach. Experts acknowledged the dispersed opinions of stakeholders on the solution proposal and provided several nuances aimed at enhancing market formation and increasing investments in the industry. Firstly, experts highlight that in order for gasification projects to be commercially attractive, projects should be developed on large scale in stead of pilot-scale to have sufficient production capacity and lower production costs through economies of scale. They also note that preserving minerals in the biomass during the gasification process is essential to retain and extract valuable residual products, such as biochar, aligning with stakeholder suggestions on improving the value chain's business case as mentioned in section 6.1.2.

Furthermore experts emphasize the importance of increasing the availability of feedstock to the value chain by diversifying partnerships and feedstock types to meet the chemical industry's demands. Hence, they indicate that exclusively focusing on network formation with players from the energy sector alone would not effectively address supply chain issues, as it would result in a limited availability of non-diverse feedstock streams. To enable a reliable, diverse, and large-scale feedstock supply, experts therefore propose strategic partnerships with players from the agricultural sector. Additionally, the experts, highlighted the essential role of Torrefaction technology in commoditizing the diverse range of feedstock streams and enabling the value chain to develop a stable and reliable supply chain.
Moreover, experts stress that as long as fossil-based chemicals remain cheaper than bio-based alternatives, the chemical industry will continue to delay investments in establishing the biomass-to-syngas value chain. They highlight the lack of financial resources and subsidies available in the market, hindering sufficient investments into the development of the value chain. Therefore, experts advocate for increased carbon pricing in the chemical industry and the development of appropriate subsidy schemes, as discussed in previous sections.

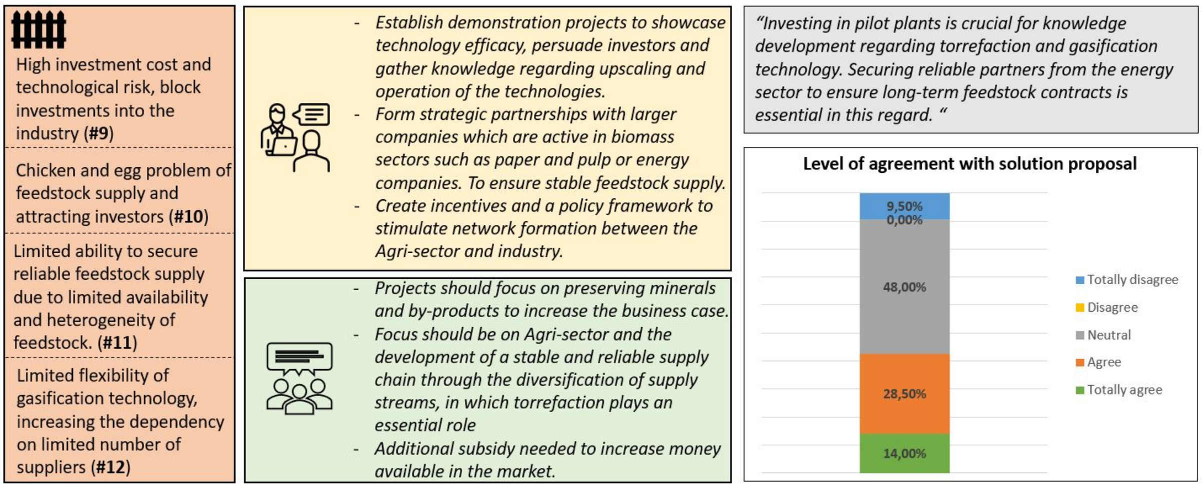

Figure 19: **Solution IV:** Strategic partnerships and pilot-plants

8.5 Solution V: Implement torrefaction into the beginning value adding steps of the value chain

As is evident from the comprehensive insights provided by industry stakeholders and experts in preceding sections, torrefaction technology has been widely recognized as a crucial component for the advancement of the biomass-to-syngas value chain. These conclusions are substantiated by the results of the live polling conducted during the webinar, in which a majority of stakeholders emphasized the essential role of torrefaction technology in establishing a sustainable and profitable value chain, as depicted in figure 20. The figure further shows how torrefaction technology holds great significance in establishing a reliable, cost-effective, and substantial supply chain by efficiently converting diverse feedstock streams into standardized and tradable commodities. Furthermore, torrefaction significantly enhances the gasification characteristics, leading to improved technological and economic feasibility of gasification projects. Integrating torrefaction technology into the value chain can therefore effectively address the barriers associated with limited access to reliable feedstock supply of consistent quality, which is often caused by limited availability and feedstock heterogeneity. Moreover, this integration overcomes the limitations of gasification technology in handling diverse feedstock streams, enabling projects to be more adaptable to various types and ratios of feedstock, reducing reliance on specific suppliers, and enhancing resilience to supply chain fluctuations or uncertainties.
During the panel discussion, a notable portion of industry stakeholders remained neutral regarding the role of torrefaction in the value chain. While these stakeholders did not state precise reasons for their neutrality, insights from interviews and the webinar transcript provide possible explanations (see appendices C.2, D and F). Some stakeholders expressed skepticism regarding the development of torrefaction technology, citing its lack of commercial breakthrough since its introduction to the market. Additionally, logistical challenges and debates surrounding decentralized torrefaction hubs, as discussed in section 7.1.1, may contribute to stakeholders' hesitancy about its implementation. However, it is important to note

that experts unanimously support the significance of implementing torrefaction technology into the value chain. They emphasize the importance of decentralized torrefaction near biomass production sources to improve supply chain logistics by reducing mass, enhancing energy-density, and optimizing feedstock storability. These experts argue that the complex logistics and technological challenges are surmountable and will not present substantial hindrances to the development of the value chain. Therefore the conclusion can be made that the implementation of torrefaction technology in the value chain can significantly contribute to the overall development and profitability of the biomass-to-syngas value chain.

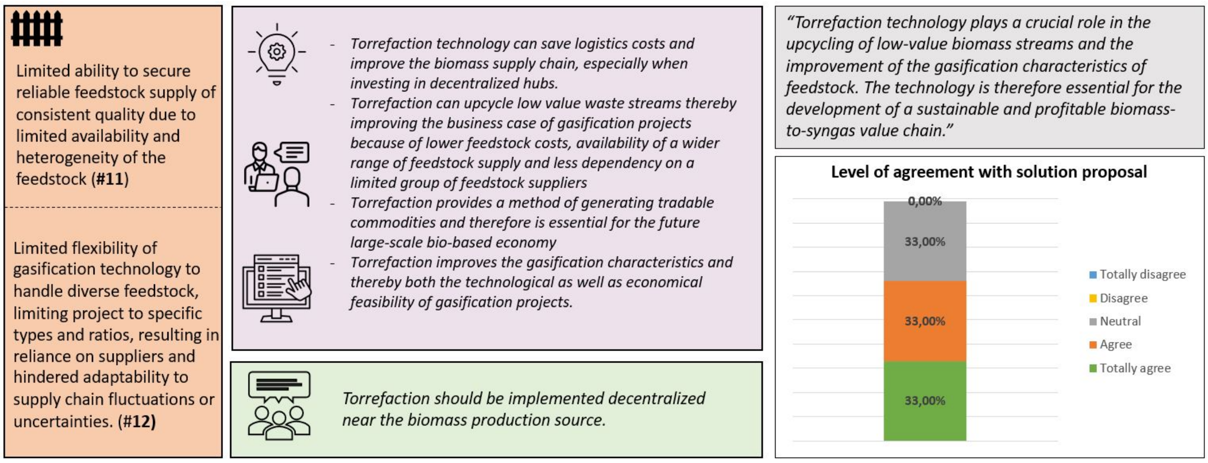

Figure 20: **Solution V:** Implementation of torrefaction

9 Discussion

Following an altered version of the stepwise approach as proposed by van Bruggen et al., led to insights regarding the SfSA approach as well as insights into the specific case of the biomass-to-syngas value chain for the Dutch chemical sector. Therefore in the sections below the conclusions and method from this research are discussed in addition to future research future research proposals.

9.1 Insights on the case study: barriers, solutions and the role and implementation of torrefaction technology

The objective of this thesis was to identify and prioritize barriers to the adoption of a biomass-to-syngas value chain in the Netherlands and formulate solutions to these barriers by exploring various stakeholder perspectives. Additionally, the feasibility and support for integrating torrefaction technology into the value chain were investigated. A step-wise and interpretive method was employed to facilitate continuous analysis and interpretation of the research results. Although the findings in section 8 already offer a thorough interpretation of the research findings, it is worth discussing some intricacies and notable aspects of the study below.

As was demonstrated in sections 3.3.1 and 7 results of the barrier identification and prioritisation process indicate that barriers to the development of the biomass to syngas value chain mainly originate from failures in the building blocks of innovation-specific institutions, network formation and coordination, and production system within the Technological Innovation System of the biomass-to-syngas value chain. Additionally the exploration of stakeholders' perceptions on the value chain's development and the prioritisation process revealed that barriers are interconnected and interactive. Meaning that barriers can cause failures in one building block which subsequently lead to failures in other building blocks. This finding aligns with the research conducted by Kirchherr et al. which also highlighted the interdependence of barriers. Hence, this finding suggests that the solution space for driving the development of the value chain predominantly revolves around these three building blocks and their corresponding solutions. Therefore to effectively address these interconnected barriers, comprehensive solution strategies were proposed to industry stakeholders and experts, as described in section 8. These solution proposals aimed to provide a holistic approach for overcoming the identified barriers in the value chain. The reflection of experts and stakeholders on these solution proposals provided interesting findings and nuances regarding their feasibility and applicability.

One interesting finding is that both industry stakeholders as well as experts believe that technological and logistical issues are surmountable and the main limiting barriers hampering the development of the value chain stem for innovation specific institutions such as the lack of economic and policy incentives, as well as an unfavorable regulatory landscape. Solution proposals aimed to enhance accessibly of governmental active investment opportunities for the bio-based chemistry sector therefore received widespread support from both industry stakeholders and experts. This widespread support clearly demonstrates that current subsidy schemes are inadequate in supporting the development of the value chain, thereby confirming the findings of section 6.2.2. Moreover, experts emphasized the necessity for cohesive policy schemes specifically aimed at enhancing the sustainability of the chemical sector. They also stressed the importance of harmonizing laws, regulations, and standards at the European level to ensure uniformity and enhance the tradability of biomass. This predominant focus on addressing regulatory, policy and economic barriers aligns with the findings of Stegmann et al. in the EU, his research also highlights institutional challenges as the key barriers to the implementation of circular strategies in small-scale bio-based markets.

Furthermore, experts and stakeholders emphasized the need to actively promote the sustainability benefits of biomass and bio-based chemical production to the general public. Building public support and facilitating the implementation of policies and subsidies are seen as crucial for fostering industry growth. The negative public perception of biomass usage in previous years has hindered the development of such measures, highlighting the significance of addressing socio-cultural factors as barriers to the value chain's development. This finding is consistent with studies conducted by the Socio-Economic Council (SER) and the Netherlands Environmental Assessment Agency (PBL), which have also emphasized the importance of addressing public perception and creating a supportive environment for the transition towards sustainable biomass and bio-based chemical production [56][59].

Apart from the emphasis on barriers stemming from failures in innovation-specific institutions, another significant barrier the study identified is the limited business case of bio-based chemicals production compared to fossil-based chemicals production. While experts highlight the need for an institutional fix, by increasing carbon pricing in the chemical sector. They also point out that the current small scale of gasification projects hinders their economic viability stressing that projects should be developed on a larger scale to achieve sufficient production capacity and lower production costs through economies of scale. Moreover, experts and stakeholders emphasize the importance of preserving valuable minerals in the biomass during the gasification process to retain and extract valuable residual products like biochar, thereby improving the business case of this production method. Additionally, experts highlight the need to enhance the availability of feedstock for the value chain by diversifying partnerships and feedstock types to meet the demands of the chemical industry. These findings indicate that addressing regulatory, policy, and economic barriers alone is not enough to drive the development of the value chain. Efforts should also focus on improving the performance of the production system and fostering network formation and coordination with players from the agricultural sector to enhance feedstock availability and improve the overall business case of bio-based chemicals production through gasification.

Another strategy to drive the development of the value chain involves the implementation of torrefaction technology near the biomass source. While the technology currently faces performance problems, experts and stakeholders emphasized that these issues can be overcome, and the focus should be on upscaling and system integration of the technology. Experts highlighted that by integrating torrefaction technology at the early stages of the supply chain, near the biomass source in a decentralized manner, significant improvements can be achieved within the value chain system. Since, this integration enables the establishment of a reliable, cost-effective, and robust supply chain by efficiently converting diverse feedstock streams into standardized and tradable commodities. Moreover, stakeholder input showed that integrating torrefaction technology into the value chain would reduce the limitations of gasification technology in handling diverse feedstock streams, enabling projects to be more adaptable to various types and ratios of feedstock, thereby reducing reliance on specific suppliers and enhancing resilience to uncertainties in the supply chain. Although, the potential benefits of torrefaction technology to the value chain have been extensively emphasized in previous academic studies such as Akbarian et al., Mamvura & Danha, and Kota et al., it is essential to consider the perspectives of industry stakeholders and experts. Their insights in this study provide valuable evidence of a strong support base within the Dutch industry for the development and implementation of this technology. Therefore, based on the industry perspectives and expert feedback, it can be concluded that the implementation of torrefaction technology in the value chain has the potential to significantly contribute to its overall development and profitability. Overall, this research contributes to existing academic literature by giving insight into the integration of torrefaction technology in the biomass-to-syngas value chain and the development of this value chain through the examination of stakeholder cooperation and perceptions along and across the supply chain. By addressing these key areas, this thesis thereby provides valuable insights and expands the existing understanding in the scientific field.

9.2 Reflection on the method

The research method of this thesis consisted of a combination of qualitative data gathering and analysis methods which were utilized to investigate the research objectives. The study followed a step-wise approach, focusing on the identification, prioritization, and analysis of barriers and solutions within the chosen context. The foundation of this approach thereby heavily relied on the SfSA framework as proposed by van Bruggen et al.. Furthermore, an additional improvement was introduced to enhance the pre-assessment step of the SfSA approach by incorporating a structured method for categorizing barriers based on the TIS building block failures, as suggested in the study of Ortt & Kamp.

While the employed research method led to a comprehensive study of the case, it is important to recognize that this study also has its limitations. By acknowledging these limitations, we can gain insights into how certain research findings might have influenced the overall validity or generalizability of the results. Moreover, the study has demonstrated the benefits and improvements of the employed framework, providing a solid foundation for future research directions aimed at addressing these limitations and further enhancing our understanding of the topic.

9.2.1 Barrier categorization method

The integration of Ortt & Kamp's TIS-building block method into van Bruggen et al.'s SfSA chain-approach has enabled a structured methodology for categorizing barriers. This integration allowed for a better quantification of the distribution of barriers and a deeper analysis of the system dynamics of the value chain. Consequently, the developed framework provided valuable insights into the performance of the value chain system and identified barriers to its development, resulting in more meaningful semi-structured interviews and analysis of stakeholder perspectives in subsequent research steps. Therefore,

the composed framework represents a clear improvement on the original SfSA-chain approach, particularly in the first two steps of the step-wise approach.
Nevertheless, the framework also introduced certain limitations to the study. One of the main limitations stems from the differences in system approaches between the SfSA method, which studies an entire value chain system and derives mutually agreed solutions through discussion and learning, and the TIS-building block method, which focuses on the dynamics of an innovation system related to the development of a single innovation. To effectively integrate these methods, certain building block definitions were expanded and modified to suit the analysis of the biomass-to-syngas value chain, as detailed in section 3.3.1.3.
However, although the modifications that were made to the building block definitions have allowed to effectively categorize the identified barriers, they also lead to ambiguities. Particularly, defining the difference between a 'product' and a 'production system' presented challenges, as technologies like gasification or torrefaction reactors can be seen as both products and production systems depending on the perspective considered. Therefore the decision was made to specify broad definitions in which the 'product' was defined as the final output of all value adding activities in the value chain and the 'production system' as the set of value adding activities and processes involved in creating a product or service. As a result, a technology could no longer be categorised as a product, which has potentially lead to an over representation of failures in the 'production system' building block and an under-representation of the 'product performance and quality' building block. For instance, barrier #2 (see table 9) , which highlights the limited flexibility of gasifier technology in producing high-quality syngas from a wide range of feedstocks, could have been categorized as a barrier related to insufficient 'product performance and quality' from the perspective of technology developers if the technology was considered solely as a product. The ambiguity in the definitions of the building blocks has therefore lead to a potential distortion in the analysis, which may impact the accuracy and validity of the findings concerning the distribution of building blocks that hinder the large-scale development of torrefaction technology and the biomass-to-syngas value chain in the Netherlands.

9.2.2 Stakeholder Engagement and Data Analysis in the Research Process

As discussed in section 3.4 , although efforts were made to engage with stakeholders through focus groups, it was observed some stakeholders were unwilling to participate. Given the limited time available for research and the logistical challenges of organizing focus groups, the decision was made to merge step 1C and 2A of the chain approach (see Figure 5), and instead conduct semi-structured interviews with stakeholders occupying diverse value-adding or supportive roles in the value chain. The data analysis method described in the coding process (see section 3.5) was therefore designed to capture a diverse range of challenges, perspectives, and opportunities from the interviews, while also addressing the exclusion of a focus group session in the research. As can be derived from section 6, this analysis method did indeed result in an adequate overview of stakeholders' perceptions on the value chain's development. Consequently, the combination of semi-structured interviews with the designed analysis method served as a suitable substitute for the original method of focus group sessions. In future research endeavors, this methodology can therefore offer a suitable approach when there is a limited time span or ability to capture a sufficient sample size for conducting focus group sessions.
In addition, it is important to note that not all stakeholder groups could be reached for participation in the interviews, particularly stakeholders from NGOs and chemical firms did not partake in the interview process. Although the involvement of industry stakeholders and experts in reflecting on the research outcomes has provided a comprehensive understanding of the case, it is important to acknowledge that, by including these additional stakeholders, the solution development process could have led to a more diverse range of solutions and potentially different prioritization of barriers. However, despite the lack of these stakeholders it is worth considering the context of the case study itself. While the absence of chemical firms in the interview population may limit the generalizability of the research findings specifically for the development of a biomass-to-syngas value chain in the chemical industry, it is important to recognize that the biomass-to-syngas value chain has applications in a range of other industries and products. Therefore by focusing on other key stakeholders such as biomass suppliers, technology developers, policymakers, and research institutions, their perspectives and insights can still provide valuable information regarding the barriers and solutions related to the biomass-to-syngas value chain. Additionally, many industry stakeholders worked closely with or in service of chemical firms, thereby allowing the inclusion of viewpoints indirectly related to chemical firms in the research.

9.2.3 Reflection on webinar

To compensate for the absence of a focus group session, a webinar was organized to facilitate expert discussion and reflection on the prioritized barriers and solutions. Additionally, approximately 21 industry stakeholders actively participated in reviewing solution proposals and providing feasibility ratings. The webinar successfully facilitated stakeholder interaction and enabled valuable discussions among experts that would have otherwise been missed without a focus group session. Additionally, this approach of expert reflection and stakeholder interaction yielded an important finding, namely that a more comprehensive and informed evaluation of solution proposals could be achieved compared to the original method proposed by van Bruggen et al.. The original method was in fact unclear whether stakeholders only assessed the impact and feasibility of the solutions presented in the literature or considered additional solutions and contextual factors unique to each stakeholder. Additionally, the discussion section of van Bruggen et al.'s research specified the challenge of formulating solutions that are specific and go beyond mere opposites of the identified problems. Therefore during the expert reflection session, the solution proposals presented were specified according to the prioritised and interconnected barriers, incorporating the insights from literature, the questionnaire and stakeholder perspectives gathered from interviews. This approach therefore ensured that the industry stakeholders and experts evaluated more comprehensive solution proposals. Moreover, the direct interaction among the experts also enabled them to collaboratively suggest refinements and nuances to the solution proposals, enhancing their effectiveness in addressing the interconnected barriers.

Whilst this approach lead to the evaluation of a more comprehensive solution proposal, it is important to acknowledge that the interpretive nature of formulating these proposals and presenting them to experts and stakeholders may have introduced researcher bias. Additionally, the profession or background of the participants in the discussion process might have influenced the outcomes and potentially affected the generalizability of the research. Although the direct interaction among stakeholders and experts facilitated lively discussions and collaboration, it is important to consider these concerns when interpreting the findings and applying them in a broader context.

9.2.4 Generalizability of research findings

In addition to the specific findings and limitations discussed in previous the reflection of the research methodology, there are additional limitations which affect the generalizability of this thesis research:

- One limitation of the data collection method is the potential for bias in the semi-structured interviews. As the interviews were semi-structured, this means that the unprepared follow up questions may have been introduced to bias. Additionally since the interviews were conducted online via video meetings this limited the ability to interpret body language and control the interview environment.

- Due to time constraint only a limited number of interviews were conducted. Although the questionnaire and webinar provided additional stakeholder input the amount of participants in this research is still relatively small for ensuring generalizability of the research findings. However, considering the exploratory nature of the research, these findings can provide an initial understanding of the topic that can be further expanded upon in future research.

- As this thesis research specifically examined the case of the development of the biomass-to-syngas value chain in the Netherlands, it is important to note that some results may lack generalizability and are specific to this particular case. For example, the issue of nitrogen deposition highlighted in barrier #11 (see table 9) is a political problem unique to the Netherlands. Additionally, the research focused on the development of a biomass-to-syngas value chain for chemical production, which means that certain findings may only be applicable to this specific route. However, since the adoption of the biomass-to-syngas value chain extends to multiple industries, some of the findings may still be applicable to other routes or cases.

9.3 Scientific contribution

This thesis significantly advances the field of scientific knowledge by studying the system integration of torrefaction technology and the development of the biomass-to-syngas value chain through the application of a novel and innovative framework. Based on the outcomes of this thesis three primary scientific contributions can be identified:

Addressing the research gap: As demonstrated in section 1.3, the current body of knowledge concerning barriers and drivers to the development of bio-based value chains for the chemical industry is lacking. This thesis addresses this research gap by identifying and examining the most significant barriers and solutions regarding the development of the biomass-to-syngas value chain through a solution-focused approach, thereby contributing to bridging the identified knowledge gap in scientific literature. Furthermore, the findings of this thesis also make a valuable contribution to the broader literature on the development of the biomass-to-syngas value chain, which are also applicable to a range of other industries.

Integration of Stakeholder Perspectives: Another significant contribution lies in the incorporation of stakeholder and expert perspectives on the development and integration of torrefaction technology in the value chain. This integration not only provides insights into the system integration of torrefaction but also offers valuable viewpoints on how to effectively incorporate the technology, thereby enhancing its overall feasibility and applicability. As highlighted by studies of Akbarian et al. and Stegmann et al., there is a need for studies that adopt a multi-dimensional approach to involve a vast array of perspectives and stakeholders to ensure comprehensive and practical solutions for sustainable transitions in industries and value chains. By engaging key actors and gathering diverse insights, this research enriches the understanding of torrefaction technology's role in the biomass-to-syngas value chain and contributes to the broader literature on sustainable transitions in the chemical and related sectors.

Innovative and enhanced SfSA methodology: This research significantly expands and enhances van Bruggen et al.'s SfSA method by integrating Ortt & Kamp's approach for identifying and categorizing barriers. The resulting novel framework provides a more comprehensive perspective on the development of the value chain, identifying critical areas and barriers that need to be addressed, and gaining insights into the dynamics of the value chain system. This innovative framework offers valuable insights into sustainability transitions and the performance of the Technological Innovation System within the value chain, making it applicable to study not only the biomass-to-syngas value chain but also other industries and value chains. However, as discussed in the previous section, the integration of Ortt & Kamp's method introduced certain ambiguities during the barrier categorization process, which future studies should take into account when utilizing this framework.

9.4 Future research

As highlighted by the limitations discussed earlier, there are areas in this thesis research that can be improved upon. Future studies should focus on addressing these limitations in order to further enhance the research and broaden the scope and generalizability of the findings. Therefore, the following recommendations are proposed for future research

Remove ambiguity from categorisation methods: In this thesis and attempt was made to improve the method of barrier identification and categorisation through the introduction of the TIS-building block framework as proposed by Ortt & Kamp. Although this method provided benefits in categorizing barriers, the ambiguity in the definitions of the building blocks has lead to a potential misrepresentation of certain building block failures in the analysis, impacting the accuracy and validity of this research.To address this limitation, further refinement of the building block definitions and clearer criteria for classification may be necessary in future research. By mitigating these ambiguities, the accuracy and validity of the analysis can be improved and therefore more reliable insights into the distribution of building blocks and their impact on the value chain's development can be gained. Therefore, future studies should consider refining the definitions and classification criteria to minimize distortions and improve the accuracy of findings.

Engage a wider range of stakeholders: Given the challenges faced in obtaining participation from certain stakeholder groups such as NGOs and chemical firms, it is important for future research to make concerted efforts to involve these stakeholders. By including a more diverse range of stakeholders, a broader perspective can be obtained, leading to a more comprehensive understanding of the barriers and solutions in the biomass-to-syngas value chain. Moreover, by including more stakeholders and respondents to the research would enhance the validity of determining the priority of barriers. Since, by incorporating a wider range of additional perspectives, the assessment of barrier prioritization would be more comprehensive and representative of the industry's viewpoints.

Conduct focus group sessions: Despite the challenges faced in organizing focus groups, the panel discussion during the webinar demonstrated the benefits of facilitating stakeholder and expert discussions. Therefore, it is recommended that future research incorporate focus group sessions into the methodology to gather valuable insights and promote the generation of new ideas from stakeholders. One particular focus group that would be valuable is a session involving NGOs and public servants focused on sustainable biomass usage. As the research findings indicate a lack of sufficient support for sustainable biomass usage stemming from these actor groups, thereby impeding policy and subsidy formation, engaging with these stakeholders through a focus group could provide valuable insights into their perceptions regarding the value chain's development and offer solutions aimed at enhancing its support base.
Expand the scope of the research: While the study primarily focused on the biomass-to-syngas value chain in the context of the chemical industry, future research should consider exploring the applicability and implications of the value chain in other industries and products. This broader perspective will contribute to a more comprehensive understanding of the barriers and solutions, and allow for comparisons and knowledge transfer across different sectors. Moreover future research should also consider investigating the system integration of the biomass-to-syngas value chain with other sustainable technologies. For instance, while this research demonstrated that electrolysers can be a competitive production system in attracting subsidy for hydrogen production, they also have potential as a complementary technology to gasification in the production of biofuels and chemicals. Therefore, conducting research on the system integration of these complementary production systems within the value chain could provide valuable insights and potentially enhance its overall performance.
Reduce researcher bias: As mentioned in the limitations of this study, the collection of data through semi-structured interviews may be susceptible to bias. Therefore, although experts reflected on the solutions and barriers derived from the interviews, it is still desirable to have the results of this study validated by other experts in the field. Future research should aim to validate the findings of this study and incorporate additional perceptions, barriers and solutions as relevant.

9.5 Practical relevance

Through the adoption of the solution-focused chain approach and active engagement with stakeholders from across the value chain this research has successfully identified barriers and proposed solutions, resulting in valuable insights that can benefit multiple stakeholder groups. Apart from offering guidance to industry stakeholders and chemical firms in their decision-making processes and operational strategies, the results also inform policymakers, researchers, and other relevant stakeholders about the challenges and opportunities within the biomass-to-syngas value chain. This thesis therefore offers practical relevance as well as possible managerial application.
Firstly the research shows that the barriers to the development of the biomass-to-syngas value chain primarily originate from failures in innovation-specific institutions, network formation and coordination, and the production system within the Technological Innovation System. By understanding the specific barriers related to these building block failures, policymakers can design targeted policy interventions and incentives to address these barriers. As the solution proposals and panel discussion in section 8 made clear, such policy interventions and incentives can consist of the formation cohesive policy schemes, harmonization of laws and regulations at the European level, increased carbon pricing in the chemical sector, and increased access to governmental investment opportunities for the bio-based chemistry sector. Introducing such measures could potentially help in driving the sustainable development of the value chain.
Additionally the study showed how public perception and support play a crucial role in facilitating a supportive environment for the implementation of policies and subsidies which help drive the development of the value chain. Both policy makers as well as industry stakeholders should therefore consider effective communication and engagement strategies, which are designed to promote the sustainability benefits of biomass and bio-based chemical production to the general public.
Another practical relevance of this report, is its ability to provide industry stakeholders such as technology developers and chemical firms with insights that can help them understand key areas in the value chain and their business processes that require attention and intervention. Based on these insights managers can subsequently develop comprehensive strategies which drive the development of the value chain. For example, managers can base their strategies on the results of section 6.1.2 and 8, which have shown how the business case of gasification projects can be enhanced through the preservation of valuable minerals as by-products, increasing the overall size of projects and diversifying partnerships and feedstock types. Additionally chemical firms can use this finding to strategically use their resources, market presence, and

financial capabilities to cooperatively develop gasification project with technology providers. Thereby transitioning their company towards sustainability and possibly gain competitive advantage by position themselves as leaders in the transition towards more sustainable practices.
Furthermore the study provides an industry perspective on the system integration of torrefaction technology in the value chain, which presents interesting findings for managers and industry stakeholders in the value chain. These stakeholders can use this information to assess the feasibility and viability of integrating torrefaction technology into their operations. Additionally these findings might convince commodity traders, such as biomass traders, to invest in torrefaction technology since the study showed that torrefaction is essential in the commoditisation of biomass streams. Thereby this could present a strategic opportunity for these actors to invest in the technology and enable large scale trade of biomass. The findings of section 7.1.1 specifically would help such companies in forming their strategies towards this technology.
In summary, this research holds practical relevance for policymakers, managers, and industry stakeholders. By incorporating its insights and recommendations, these stakeholders can drive the development of sustainable bio-mass to syngas value chain, contributing to the transition towards a more sustainable and circular economy.

10 Conclusion

The overall goal of this thesis was to identify and prioritize barriers to the adoption of a biomass-to-syngas value chain in the Netherlands. By investigating diverse stakeholder perspectives, the research aimed to formulate effective solutions to the identified barriers. The research thereby provided valuable insight into the viability of scaling up the biomass-to-syngas process and its potential implications for the growth of the bio-based chemical industry in the Netherlands. Furthermore, the research also explored the role and impact of incorporating torrefaction technology, aiming to assess its potential value-addition and contribution to the overall development of the biomass-to-syngas value chain. Therefore the following research question stood central during this thesis research:

What strategies can be implemented to effectively drive the development of the biomass-to-syngas value chain for bio-based chemical production in the Netherlands, taking into account industry stakeholders' perspectives, key barriers, and mutually derived solutions?

To address the research question, a step-wise approach was followed, incorporating specific sub-questions that targeted different aspects of the biomass-to-syngas value chain's development. Data was collected from various sources and methods, including an exploratory literature review to identify barriers, and semi-structured interviews with eight stakeholders representing different segments of the value chain. Moreover, based on the identified barriers and stakeholders' perspectives from the interview, a questionnaire was used to gather insights on the significance of the barriers and additional solution proposals. Lastly, a webinar was organized, serving as a panel discussion platform to gather nuanced insights and further explore comprehensive solution proposals aimed at overcoming the most significant barriers blocking the value chain's development. By accumulating insights from this approach, a comprehensive understanding of the biomass-to-syngas value chain was obtained, enabling the formulation of effective strategies to drive its development.

The research findings have highlighted 44 interconnected barriers that impede the development of the biomass-to-syngas value chain. These barriers primarily stem from failures in innovation-specific institutions, network formation and coordination, and the production system within the Technological Innovation System of the value chain. The interactive nature of these barriers hamper progress in various sections of its development, therefore it is essential to develop comprehensive solution strategies that specifically target the identified obstacles. Moreover, another important insight from the research is the consensus among stakeholders and experts that technological and logistical issues can be overcome, and the finding that the major barriers to the value chain's development are primarily rooted in the failures of the building block innovation-specific institutions. These failures in innovation specific institutions result in an absence of economic and policy incentives, as well as an unfavorable regulatory landscape. Addressing these barriers is therefore vital to drive the development of the value chain. Therefore, building upon these valuable insights and incorporating input from stakeholder interviews and expert discussions, the following five key strategies have been formulated, aimed at effectively driving the development of the value chain.

1. Cohesive policy formation

The research findings emphasize the importance of developing cohesive policies to address barriers resulting from policy failures. These barriers, including political uncertainty, lack of long-term policy, and unpredictability in climate policy, have hampered the market development of biomass gasification projects. Therefore in order to overcome these challenges, the findings suggest that policy formulation at the EU level is essential to enhance the sustainability of the chemical sector. Stakeholders emphasized that considering the global nature of the industry, policy design should therefore also encompass its international scope. Moreover, implementing policies at the European scale would enable a comprehensive and coordinated approach to driving the industry's sustainable transition and facilitating the development of the value chain. However, achieving cohesive policy formation requires collaboration across the entire value chain, involving policymakers, industry stakeholders, and academia. This collaboration should aim to establish a consistent and clear stance from policymakers regarding sustainable biomass usage, while also raising awareness among the general public about the potential of biomass as a scalable and sustainable source for chemical building blocks.

2. Industry-tailored subsidies

In addition to policy failures, inadequate financial support and subsidy schemes are identified as significant barriers to the development of the value chain. The research highlights the need for tailored industry subsidies to overcome these barriers. Therefore stakeholders and experts strongly support the implementation of a comprehensive subsidy scheme that covers both capital expenditures (CAPEX) and operational expenditures (OPEX). By providing sufficient financial support, this strategy aims to mitigate short-term risks associated with high capital investments and support the development of projects at a larger scale. Additionally, it would facilitate the acquisition of long-term feedstock supply contracts and build investor trust, ultimately driving the development of commercial-scale gasification projects and the overall value chain. Customized subsidy schemes specifically tailored for the bio-based chemistry sector are hence considered essential to drive the development of the value chain.

3. Implement uniform law and regulations

Apart from inadequate subsidy schemes and policy failures, complex permitting processes and inconsistent certification schemes are also identified as significant barriers resulting from failures in innovation-specific institutions. These barriers impede technology providers from attracting investments and limit the tradability of feedstock. To overcome these challenges, a strategy was derived from stakeholder and expert input focused on enhancing the uniformity of regulations and certifications. This strategy involves the development of uniform laws and regulations at the EU level and the establishment of international standards. By addressing existing inequalities and establishing a level playing field between biomass and fossil fuels, this strategy aims to improve the tradability of biomass feedstock and facilitate trade. However, to facilitate the development of comprehensive and harmonized regulations, it is crucial to enhance knowledge and awareness of biomass technologies, their applications, and market potential among policymakers, industry professionals, and academia. By implementing this strategy, a more favorable regulatory environment can be created that enables the development of the biomass-to-syngas value chain and facilitates the growth of the bio-based chemical industry.

4. Enhance network formation and coordination through strategic partnerships

Moreover, besides institutional failures the research revealed that limited network formation and coordination, and insufficient performance of gasification technologies are also significant obstacles to the development of the value chain. To address these challenges, a comprehensive strategy was proposed, focusing on enhancing the business case and network formation. This strategy includes developing gasification projects on a commercial scale to achieve production capacity and cost efficiencies, preserving valuable minerals during the gasification process to extract residual products like biochar, and establishing strategic partnerships with agricultural players for a diverse and reliable feedstock supply. By addressing these aspects, the strategy aims to overcome regulatory, policy, and economic barriers while improving the overall business case for bio-based chemicals production through gasification.

5. Decentralized integration of torrefaction technology

Furthermore, another important finding of the research is the wide support base of industry stakeholders and experts for the implementation of torrefaction technology in the value chain. Based on expert insight the proposed strategy suggests integrating torrefaction at the early stages of the supply chain in a decentralized manner. This approach thereby addresses challenges related to feedstock supply, logistics, and standardization. Experts highlight the benefits of torrefaction, including improved supply chain efficiency, increased energy density, and optimized feedstock storability. Although some concerns exist regarding the logistical challenges of a decentralized supply chain, experts believe that these obstacles can be overcome. By integrating torrefaction technology, the strategy therefore aims to enhance system performance, achieve standardized commodities, and improve the overall profitability and resilience of the biomass-to-syngas value chain.

In conclusion, this thesis provides valuable insights into the barriers and solutions regarding the development of the biomass-to-syngas value chain for bio-based chemical production in the Netherlands. The proposed strategies offer a roadmap for driving the value chain's development and increasing the sustainability and growth of the bio-based chemical industry. With further collaboration, implementation, and continuous research, the Netherlands can position itself as a leader in the utilization of biomass resources and contribute to a more sustainable and resilient future. However, it is important to recognise that this thesis has primarily focused on the specific context of the Netherlands, hence the findings may not be directly applicable to other regions or countries with different socio-economic and regulatory landscapes. Future research could therefore explore the generalizability of the identified barriers and strategies to other contexts and aim to create a more universal understanding of the challenges and opportunities in scaling up biomass-to-syngas value chains. Moreover, further research is needed to address specific aspects, such as the economic feasibility of the proposed strategies, the environmental impacts of the value chain, and social acceptance of biomass technologies. By expanding the knowledge base in these areas, policymakers, industry stakeholders, and researchers can collaborate to overcome the barriers and unlock the full potential of biomass-to-syngas value chain for the production of sustainable chemicals.

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A Methodology Details

A.1 Interview protocol

Prior to the interviews, participants were provided with various materials, including an invitation to participate, a study abstract and a consent form. They were reassured that the study would have minimal impact on them and that their confidentiality would be upheld. Consequently, the participants will not be named by name in this study in order to uphold their privacy. In total, eight semi-structured interviews were conducted via teams with the selected participants. The interviews took place over a period of approximately one month, from mid-march till mid-April. The total duration of recorded interviews amounted to 8 hours and 23 minutes, resulting in 82 pages of transcripts for subsequent analysis. The length of individual interviews varied, ranging from 24 minutes to 1 hour and 34 minutes.

A.1.1 Interview scheduling

Participants were found using the network of the internship company Uniper and through the snowballing method, were participants referred through to new potential participants. Overall 5 participants were stemming from Uniper's network and three based on referral. The participants were contacted e-mail and telephone using the process for interview scheduling as depicted below.

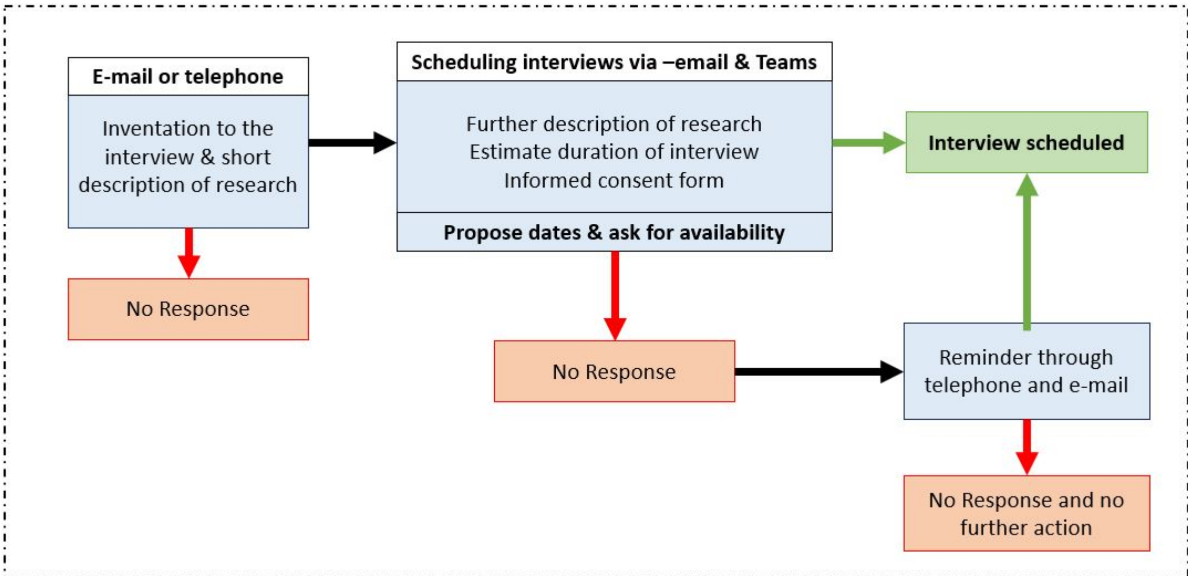

Figure 21: Interview scheduling

A.1.2 Interview questions

The interviews were designed to facilitate open and conversational atmosphere, encouraging stakeholders to freely express their perspectives on the development of the value chain. To maintain consistency in the responses, a list of potential questions was prepared and utilized as a reference during the interviews, which is elaborated below. It is important to note that these questions were not the sole focus, as interviewers also employed interview-specific and follow-up inquiries tailored to each conversation. However, the questions listed below were frequently asked and have contributed significantly to the valuable insights that were obtained in this study.

- Could you provide a description of your role and your company's activities?
- What are the currently the major issues in developing gasification/torrefaction technology?
- How feasible is it for a relatively small technology developer to penetrate the market compared to established companies with sufficient capital?
- What do you see as the biggest obstacles to the development of the value chain in the coming years?

- How do you assess the feedstock market and obtaining reliable biomass streams amidst competition from the pulp and paper industry and energy sector?
- How do you view the impact of politics and public debate on the development of the bio-based sector?
- What What is your assessment of the level of demand and support for investing in the development of your technology?
- What do you see as the biggest obstacles for the development of the biomass-to-chemicals value chain in the coming years?
- What is your opinion regarding torrefaction technology and its potential impact on the industry?
- Is there anything you feel should have been asked or any additional information you would like to share?

B References literature review

Using the search terms specified in 3.3 scientific and grey literature was found regarding the biomass to syngas value chain and torrefaction. This resulted in obtaining the following list of 15 scientific sources and 16 gray-literature sources. Two different citation methods where used to allow differentiation of scientific and grey literature sources in the barrier overview in Appendix C.

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C Barriers

C.1 Barrier overview

In table 9 below an overview of all barriers to the development of the biomass-to-syngas value chain and torrefaction is shown. These barriers were derived from literature and stakeholder interviews. Barriers which were mentioned by interviewees are marked according to their reference in this thesis as specified in Table 3. Additionally two different citation methods were used to differentiate scientific and grey literature sources from each other. Barriers are categorised by the actor(s) facing the barrier as specified in section 4.1, and the TIS-building block and influencing condition which are linked to the barrier .

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
1	Knowledge institution & Technology developer	Limited technical ability and knowledge to produce high quality syngas from biomass and biochar	Production system	Knowledge and awareness of technology	[61], [16], [AAK+22], [SRT17], [GSJG23]
2	Knowledge institution & technology developer	Limited flexibility of gasifier technology to obtain high quality syngas out of wide range of feedstocks.	Production system	Knowledge and awareness of technology	[61], [16], [AAK+22], [SRT17], [B][D][E][F][H]
3	Chemical firms & technology developers	Biochemicals produced through gasification of (torrified) biomass is unable to compete with fossil-fuel based chemicals	Product price	Competition	[13], [4], [15], [3], [LYZ+21], [D][E][H]
4	Governmental institutions & certification offices	There is a lack of product standardisation causing the market to be unreliable and nontransparent	Innovation specific institutions	Knowledge and awareness of application and market	[10], [14], [11]
5	Governmental institutions & certification offices & technology developer	Due to public debate and subsequently low policy attention there are no certification and subsidy schemes that focus on bio-genic syngas production for the chemical sector	Innovation specific institutions	Macro-economic and strategic aspects	[2], [9], [7],[D][E][F][G]
6	Governmental institutions & chemical firms	Lack of both EU and NL long term policy specifically aimed at the chemical sector, causing uncertainty regarding sustainability in the chemical market and a lack of investments	Innovation specific institutions	Macro-economic and strategic aspects	[5], [7], [8], [13], [12], [SRT17], [LYZ+21], [MAM+22], [OMN+21], [D][E][F][G]
7	Certification offices & Branch and advisory organisations	Many stakeholders view the current subsidy and certification schemes as not reliable and question the practicality and enforcement of these schemes, therefore companies are reluctant to apply since they expect a low-win opportunity in these schemes	Network formation and coordination	Socio-cultural aspects	[16], [13], [12], [B][C][D][E]
8	Biomass traders & governmental institutions	Strict import restrictions to safeguard the sustainability of the feedstock. Result in increased complexity and high cost for the business sector and regulating parties, and a limited tradability of biomass	Innovation specific institutions	Macro-economic and strategic aspects	[13], [12], [A]

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Table 9 – continued from previous page

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
9	Governmental institutions & certification offices	There is uncertainty to which extent nations can create additional criteria and legislation at national level regarding the importation and certification of biomass. Causing national policies to lack the customisation required for their case/region.	Innovation specific institutions	Knowledge and awareness of application and market	[13], [12]
10	Governmental institutions & NGO's & Branch organisations	Insufficient connection to cascading principle: Many stakeholders believe that current policy instruments and subsidy arrangements insufficiently connect to the cascading principle and therefore do not advocate for the up-cycling of biomass/waste.	Innovation specific institutions	Knowledge and awareness of application and market	[13], [12]
11	Governmental & NGO's	Nitrogen crisis leads to increased public debate and political uncertainty regarding the future of building/biomass projects making businesses and investors hesistant to invest in new projects	Innovation specific institutions	Socio-cultural aspects	[2], [1], [5] [A][C][D][F][H]
12	Governmental institutions & NGO's	There is high political uncertainty surrounding the use of biomass due to a strongly polarised public debate. Resulting in limited policy attention regarding the development of biomass-to-x technologies	Network formation and coordination	Socio-cultural aspects	[6], [13], [12], [LYZ+21], [3] [A][C][D][F][H]
13	Governmental institutions & chemical firms	Due to political uncertainty and fast changing climate policies there is high uncertainty among industry and investors regarding future biomass projects resulting in a lack of investments and partnerships	Network formation and coordination	Natural, human and financial resources	[6], [13], [12], [LYZ+21], [3] [A][C][D][E][F][H]
14	Chemical firms & Governmental institutions	Limited circulair behaviour of chemical firms due to path dependency and business model of short term profit seeking and dividend payments to shareholders does not advocate for a transition to sustainable production	Customer	Socio-cultural aspects	[12], [B][E]
15	Governmental institutions & technology developers	There is lack of awareness and non-uniformity of knowledge base regarding gasification technology among industry, institutions, local bodies, consumers, and entrepreneurs. hindering the further exploitation of biomass applications ultimately leading to market failures	Network formation and coordination	Knowledge and awareness of application and market	[SRT17], [LYZ+21], [6], [GSJG23] [A][B][D][E][F]

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Table 9 – continued from previous page

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
16	Biomass trader	Limited ability to secure reliable feedstock of consistent quality due to heterogeneity and non-availability of feedstock	Product performance and quality	Natural, human and financial resources	[61], [16], [36], [7], [6], [AAK+22], [GSJG23] [A][C][D][E][F]
17	Biomass traders	Expensive supply chain . Due to large bulk size, seasonal dependence and limited storability of raw biomass	Product performance and quality	Natural, human and financial resources	[61], [16], [36], [8], [SPRT17], [SZF+17], [LYZ+21] [A][F]
18	Biomass traders & Branch organisation	Limited possibilities for local (Dutch) sustainable biomass production due to limited amount of space	Production system	Natural, human and financial resources	[5], [13]
19	Governmental institutions & NGO's	The production of sustainable biomass can have negative (and sometimes positive) consequences for biodiversity.	Production system	Socio-cultural aspects	[13]
20	Biomass traders & Business sector	Insufficient connection between the agricultural sector and chemical sector. Causing a discrepancy between sustainable biomass production and biochemicals innovation projects. At the moment there is a coordination/system failure	Network formation and coordination	Macro-economic and strategic aspects	[61], [16], [36], [7], [6], [AAK+22], [GSJG23], [3]
21	Customers & Biomass-to-X	Chemical companies can be hesitant to invest and cooperate in sustainable chemical production projects due to path dependency and potential knowledge spillovers	Customer	Macro-economic and strategic aspects	[3] [B][E][F]
22	Chemical firms & Governmental institutions	Limited carbon pricing a specifically aimed at the chemical industry, withholding investments in sustainable production and upholding the current exploitation of fossil fuels	Innovation specific institutions	Macro-economic and strategic aspects	[5], [7], [8], [13], [12] [B][C][D][H]
23	Biomass traders & technology developers	Technology providers of BtX-projects are unable to obtain long-term feedstock contracts, due to their limited market share, which are needed as leverage to attract external investors	Network formation and coordination	Natural, human and financial resources	[A][C][D][E][F][G]
24	Technology developers & biomass traders	The lack of investments in BtX projects withholds growth of this sector and subsequently the possibility of obtaining long term feedstock contracts.	Network formation and coordination	Natural, human and financial resources	[A][C][D][E][F][G]
25	Entire value chain	Ukraine war led to increased market uncertainty and volatile material prices resulting in a wait-and-see mentality amongst investors	Network formation and coordination	Accidents and events	[H]

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Table 9 – continued from previous page

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
26	Chemical firms & technology developers	Competition of electrolyser technology in hydrogen projects results in lacking investments. Since electrolyser technology obtains more subsidies and is a less uncertain investment in the political sense.	Production system	Competition	[D][E]
27	Technology providers & biomass traders	Due to limited market power BtX sourcers are unable to impose the required sustainability demands, thereby preventing the build up of secure and sustainable supply chain and new partnerships	Network formation and coordination	Macro-economic and strategic aspects	[A]
28	Governmental institutions & certification offices	The singular emphasis on sustainability has led to an excess of regulations and certifications flooding the market, which has made the value chain more complex to build.	Innovation specific institutions	Socio-cultural aspects	[A][C][E][H]
29	Certification offices & technoology providers	Complicated and slow permitting schemes slow down projects and form a administrative and financial barriers for SME technology providers	Innovation specific institutions	Natural, human and financial resources	[D][G][H]
30	Chemical firms & technology providers	Investors are hesitant to invest in torrefaction and gasification technologies due to high capital expenditure and high technological risk regarding up-scaling of technologies leading to limited development of biomass-to-syngas projects	Production system	Natural, human and financial resources	[16], [36], [16], [9], [7], [8],[SAK+20], [LYZ+21], [AAK+22] [B][C][D][E][F][G]
31	Governmental institutions & branch organisation	The term 'biomass' is much to broad and has a negative stigma. Thereby not allowing for the distinction of sustainable feedstock streams and negatively contributing to the public image of biomass.	Innovation specific institutions	Knowledge and awareness of application and market	[A][B][D][E][F]
32	Technology developers & chemical firms	Lack of trained technical personnel hampers technology development	Network formation and coordination	Natural, human and financial resources	[F]
33	Knowledge institutions & technology developer	Low technological maturity and a lack of knowledge regarding the up-scaling of gasification technology resulting in high technical risk	Production system	Knowledge and awareness of technology	[61], [16], [36], [9], [6], [AAK+22] [B][C][D][E][F]

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Table 9 – continued from previous page

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
34	Governmental institutions & technology developers	Subsidies do not properly cover the investment risks of torrefaction and gasification projects and do not support the development of commercial scale projects. Therefore there is mismatch subsidy schemes and what is needed for development of the value chain. resulting in a lack of investments	Innovation specific institutions	Natural, human and financial resources	[16], [36], [5], [16], [9], [7], [8], [SAK+20] [C][D][E]
35	Technology developers	Underdeveloped market of technology providers, only small number of manufacturers	Network formation and coordination	knowledge and awareness of technology	[AAK+22] [A][C]
Torrefaction specific barriers					
36	Technology developers	Limited flexibility of torrefaction technology to process biomass with varying properties	Production system	knowledge and awareness of technology	[61], [16], [AAK+22], [MAM+22], [OMN+21], [E][F]
37	Technology developers	The content of inorganic compounds in ash increases during torrefaction, which limits the utilization of torrefied biomass in gasification and combustion practises	Product performance and quality	Knowledge and awareness of technology	[16], [36], [SAK+20], [GSJG23] [F]
38	Technology developers	During torrefaction tar contents increase, which increases the possibility for tar and slack formation resulting in an increased risk of operational issues	Production system	Knowledge and awareness of technology	[16], [NND21], [SRT17], [AAK+22], [MAM+22], [E][F]
39	Technology developers	Torrefied pellets are currently more expensive than incumbent wood pellets.	Product price	Competition	[16], [NND21], [A][G]
40	Governmental institutions & technology developers	Lacking regulatory framework regarding distribution and processing of 'waste-streams' and torrified materials increasing complexity of setting up the supply chain of waste-to-x projects	Innovation specific institutions	Knowledge and awareness of application and market	[5], [10], [11], [14]
41	Technology developers & Biomass-to-X	Self-heating problem. Torrefied material has coallike properties, thereby increasing the odds for self-ignition. Storage facilities have to be adjusted for this phenomenon creating different supply chain dynamics than for 'normal' biomass	Product performance and quality	Knowledge and awareness of application and market	[16], [NND21], [8]
42	Technology developers	Process interruptions occur frequently due to technical challenges in achieving constant and well controlled process conditions for the production of a uniform product	Production system	Knowledge and awareness of technology	[61], [SRT17], [SZF+17], [LYZ+21]

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Table 9 – continued from previous page

#	Actor(s)	Barrier	Building block	Influencing condition	Source / interviewee
43	Technology developersr	Torrified biomass is difficult to densify and pelletise, leading to higher operational costs in comparison to raw biomass processing and limiting transportability	Product performance and quality	competition	[61], [NND21] [F]
44	Technology developers & knowledge institutions	Low technological maturity and a lack of knowledge regarding the up-scaling of torrefaction technologies resulting in high technical risk	Production system	Knowledge and awareness of technology	[61], [16], [36], [9], [6], [AAK+22] [B][C][D][E][F]

Table 9: Barriers Biomass-to-X

C.2 Interview analysis - Barrier-themes

In this section the themes and barriers derived from the semi-structured interviews with stakeholders from across the value chain are included. These themes, sub-themes and barriers were identified using the grounded theory analysis method described in section 3.5.

C.2.1 Market development

Sub-theme	Barrier	Interview term or quote
Lack of investments	Investments are lacking due to high technical uncertainty coupled to high investment risks	"Problemen met aantrekken investeerders" [B] [D]"kleine bedrijven krijgen lastig financiering, hoge investeringsrisico's" [F] "lage technologische volwassenheid vergassingstechnologie" [D] [E] "onderontwikkelde markt" [F] "technisch risico houdt investeringen tegen" [E] "onzekerheid van de markt" [G] "opschaling belemmerd door supply-chain" [F]
	Investors and chemical firms are hesitant to invest in BtX due to lack of political consensus surrounding biomass technologies	"Onzekere investering" [A] "Gebrek aan politieke consensus gebruik biomassa" [C] "terughoudendheid financierders wegens maatschappelijk debat" [C] "Publiek debat maakt het moeilijk om grote investeerders aan te trekken"[D] "zeker last van die discussie"[E] "Maatschappelijk debat werkt ontwikkeling markt tegen" [F]
	There is a barrier for technology providers in attracting external financing since their limited market size prevents them from obtaining long-term feedstock contracts which are needed as leverage to attract external financing	"Moeilijk verkrijgen lange termijn feedstock contracten"[A][D]"Lastig markt betreden als SME"[A] "trage opstart agrisector"[C]"grootste bottleneck is biomassa leverancier"[D] "Lastig om constante stroom feedstock te verzekeren"[E] torrefactie/gasificatie bedrijven te klein voor marktpenetratie [F]"Langdurige afname contracten niet mogelijk ivm technologisch risico" [G]
	Ukraine war led to increased uncertainty and material prices resulting in a wait-and-see mentality amongst investors	"Oekraïne oorlog heeft investeerders afwachtend gemaakt" [H]
Policy failures	Slow and complicating licensing slows down projects and makes investors hesitant to invest	"Extra kosten certificering"[A] "Certificeringsprocedure(s) te lastig voor SME" [C] "Onevenredig hoge transactiekosten biomassa" [C] "Overvloed certificeren bemoeilijkt opbouw keten" [G] "Verkrijgen vergunningen lastig" [G] "Gebrek aan investeringen door ingewikkelde vergunningstrajecten" [H]

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Table 10 – continued from previous page

Sub-theme	Barrier	Interview term or quote
	Investors are hesitant to invest due to lacking subsidy schemes and the uncertain political environment	"Huidige subsidieregeling schiet te kort in het aantrekken/overtuigen van investeerders" [D] "Moeilijk om subsidie te krijgen" [D] "Mismatch tussen de steun/subsidies en wat ervoor nodig is om het risico af te dekken" [E] "Complexe subsidieverstrekking vanuit de overheidspartijen" [F] "Risico's van grote investeringen niet gedekt gecombineerd met hoge onzekerheid" [G]
Business case	Minimal business case of biomass gasification projects compared to incumbent technologies	"Minimale of zelfs negatieve business case" [E] "Zonder die drive hebben wij ook geen business case" [H]
	Competition of electrolyser technology in attracting subsidies hampers business case BtX	"men vindt elektrolyse een betere investering vanwege de onzekerheid rond" [D] concurrentie elektrolyse [E]
	Normal wood pellets are less expensive than torrified pellets	"Gewoon al een werkend product/keten namelijk hout-pellets" [A] [G]
	Fossil based chemicals are less expensive to produce than bio-based chemicals	"Bio-based duurder dan fossil-based" [B] "concurrentie fossiele brandstoffen" [D]
	The technology market of gasification and torrefaction is underdeveloped resulting in limited demand for the technologies and subsequently limited technology development	"onderontwikkelde markt" [A] [F] "weinig realisatie van torrefactie projecten" [C]

Table 10: Market development

C.2.2 Supply chain

Sub-theme	Barrier	Interview term or quote
Security of supply	Gasification and torrefaction producers and projects lack the market power to obtain a reliable and consistent feedstock stream	"Afhankelijkheid internationale biomassa stromen" [A] "moeilijk verkrijgen betrouwbare stroom" [A] "Lastig verzekeren van constante stroom feedstock" [D] [E] "opschaling belemmerd door supply-chain" [F] "lastig betreden markt" [A] [D] "hoge onzekerheid feedstock markt" [D] [H] "torrefactie/gasificatie bedrijven te klein voor marktpenetratie" [G] "Lastig om feedstock supply vast te leggen door kleine schaal projecten en grote geweld pulp& paper" [F]
Cost performance	Raw biomass characteristics result in an expensive and uncertain supply chain increasing feedstock costs.	"Dure vracht"[A] "Onzekerheden aanvoer door heterogeniteit" [A] "Volatiliteit" [A] "Transport problemen biomassa"[F]
Sustainability	Due to limited market power BtX sourcers are unable to impose the required sustainability demands, thereby preventing the build up of secure and sustainable supply chain and new partnerships	"Beperkte marktpositie voor opleggen sustainability eisen" [A]

Table 11: Supply chain development

C.2.3 Policy and subsidy

Sub-theme	Barrier	Interview term or quote
Public debate	There is a lack of political consensus regarding biomass use resulting in a lack of policy-decissions regarding biomass-to-chemistry	"maatschappelijke gepolariseerd debat biomassa"[A][C][D]"Negatieve framing"[A]"zwalkend beleid" [B] "Gebrek aan politieke consensus gebruik biomassa" [C] "Te weinig daadwerkelijke acties politiek" "Biogene opwekking chemicaliën wordt vaak overgeslagen in beleidsstukken" [D] [C]"Maatschappelijk debat belemmering opzet waardeketen" [F] "Chemische sector onderbelicht in beleid"[D] [H]
	Public debate complicates the formation and issuance of subsidies to biomass projects	"moeilijk subsidie te krijgen door maatschappelijk debat" [D] "Maatschappelijk debat belemmering subsidie en wet-en regelgeving" [F]
	There is a lack of widespread knowledge regarding sustainable biomass streams which negatively affects the public debate	"beperkte maatschappelijke/breedgedragen kennis sustainability biomass"[A] [B] [D] [E] [F]"Gebrek aan voorlichting en kennis over duurzame biomassa stromen" [B] "kennis is niet wijd verspreid" [E] "in nederland hebben we geen idee wat biomassa is"[F]
	The term 'biomass' is much to broad and has a negative stigma. Thereby not allowing for the distinction of sustainable feedstock streams and negatively contributing to the public image of biomass	"Negatieve framing"[A][F] "Te brede term biomassa" [B][E][F] "Misconceptie dat biomassa leidt tot boskap en verbranden van bomen" [D]
Excessive focus on sustainability	There is an excessive amount of focus on sustainability in policy making and too little on building value-chains. Negatively affecting policy- and subsidy formation	"Te grote focus duurzaamheid, te weinig op opzetten value-chains"[A] [C][E][H] "Overmatige politieke en regelgevende aandacht voor duurzaamheid vertraagt de ontwikkeling van projecten" [H]
Effectiveness policy and subsidy	No subsidies aimed at syngas (or biochemicals) due to limited measurability of the impact	"Syngas is een tussenproduct waardoor de waardetoevoeging ervan lastiger te meten is" [G]
	Mis-match subsidy schemes and what is needed for development of the value chain. Lacking subsidies to cover short-term risks. Resulting in lack of investments in the industry.	"Uitblijven van subsidie"[C] "Huidige subsidieregeling schiet te kort in aantrekken van investeerders" [D]" Specifiek biogene waterstof wordt gemist of uitgeschreven uit subsidie regelingen" [D] "Subsidies dekken investeringsrisico's niet goed" [E]
	Fast changing (inter)national policies lead to uncertainty regarding projects, making investments in the industry uncertain	"zwalkend beleid" [B] "Gebrek aan politieke consensus gebruik biomassa" [C]"Beleid zeer veranderlijk"[H]
Path dependency	(stock) Market-structure of short-term profit seeking and dividend payments does not advocate for a transition to sustainable production	"te weinig ontmoediging fossiel"[B] "Korte termijn focus bedrijven weerhoudt versnelling grondstoffen transitie" [B][E]

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Table 12 – continued from previous page

Sub-theme	Barrier	Interview term or quote
	There is a lack of policies specifically aimed at addressing the carbon footprint of the chemical industry. This results in a lack of motivation for companies in the sector to prioritize sustainability initiatives, hindering progress towards a more sustainable industry.	"te weinig ontmoediging fossiel"[B]"zware lobby vanuit petro-chemische sector"[C]"Chemische sector onderbelicht in beleid "[D] "Gebrek en wet-en regelgeving specifiek voor chemie belemerd drive veruurzaming"[H]

Table 12: Policy and subsidy

C.2.4 Law and regulation

Sub-theme	Barrier	Interview term or quote
Regulatory Overload	The singular emphasis on sustainability has led to an excess of regulations and certifications flooding the market, which has made the value chain more complex to build	"Te veel regels en wetgeving" [B] "Hele gelimiteerde focus op duurzaamheid leidt tot te strakke wet-en regelgeving waarmee de waardeketen vast gezet wordt"[C]ingewikkelde wet- en regelgeving, grote belemmering voor producenten [C] "Overmatige focus op sustainability in regelgeving"[H] "Extra kosten certificering" [A] "certificeringsprocedure(s) te lastig voor SME" [B] "onevenredig hoge transactiekosten biomassa" [C] "Overvloed certificeren bemoeilijkt opbouw keten" [G]
	Complicated and slow permitting schemes slow down projects and form a barrier for SME's due to increased transaction costs and increased administrative pressure	"Onevenredig hoge transactiekosten biomassa" [C] "Verkrijgen vergunningen lastig" [G][D] "Ingewikkelde en langdurige vergunnigsprocedures" [H]
	Tradability of biomass feedstock is difficult due to varying regulations and certifications per country	"Verschillende import behandeling per biomassa stroom" [A] "Verschillende wet-en regelgeving & certificeringen per land bemoeilijken tradability" [A]

Table 13: Law & regulation

C.2.5 Technological issues

Sub-theme	Barrier	Interview term, quote or source
Up-scaling issues	High technological and commercial uncertainty surrounding up-scaling of technologies	"Operationele problemen opschalen" [B] "Te weinig bewijs dat de technologieën werken en kunnen worden ingezet." [C]"Zorgen omtrent opschaling vergassingstechnologyie" [D][E] "Gebrek aan commerciële kennis omtrent gasificatie" [E] "Operationele problemen bij opschaling torrefactie technologie" [F] "Hoge kapitaalkosten voor grote/specifieke installaties" [F]
	Low technological maturity resulting in operational issues and high technological uncertainty	"Lage technologische volwassenheid vergassingstechnologie"[D][E] "Torrefactie technologie nu TRL 7-8" [B][F]
Flexibility to process varying feedstock streams	Limited flexibility of gasifier technology to obtain high quality syngas out of wide range of feedstocks.	"Problemen met de kwaliteit van het syngas" [B]"Heterogeniteit biomassa creëert onzekerheid in opzetten processen"[D] "Beperkte feedstock stromen bruikbaar voor bepaalde kwaliteit syngas en char"[E][F][H]
	Several different reactor types exist for each technology. Each having their own pros and cons and limitations regarding feedstock range it can process. No dominant design has emerged yet.	"veel verschillende technologieën/gasificatie methoden die nog niet bewezen zijn" [D][E][F]
	Limited flexibility of torrefaction technology to process wide variety of feedstocks	"Niet alle biomassa stromen kunnen in dezelfde reactoren behandeld worden (torrefaction) [E][F]
Operational issues	Operational issues such as tar and slack formation in gasifiers.	"Teer en slack problemen"[E]
	Operational issues such as tar and ash related issues in torrefaction units.	"Teervorming is een bekend probleem in een torrefactie installatie" [F]
	High temperatures and structural changes during torrefaction can result in the material being difficult to form into pellets.	"Problemen met pelletiseren"[F]
R&D	Lack of transparancy of chemical firms in cooperative projects results in slower R&D and technology development	"Het gebrek aan openheid van bedrijven in de samenwerking" [B]"Technologische kennis niet wijd verspreid met een gebrek aan kennis op het gebied van commerciële toepassingen" [B][E][F]
	Lack of trained technical personel hampers technology development	"Goed personeel krijgen is lastig, er zijn niet zo veel techneuten"[F]

Table 14: Technological issues

D Solutions

D.1 Interview analysis - Solution-themes

In this section the themes and solution derived from the semi-structured interviews with stakeholders from across the value chain are included. These themes, sub-themes and solutions were identified using the grounded theory analysis method described in section 3.5.

D.1.1 Solutions to increase market development

Sub-theme	**Solution**	**Interview term, quote or source**
Demo Projects for investor persuasion and improving industry-knowledge	Establishing demonstration projects to showcase technology efficacy, persuade investors, and gather knowledge on up-scaling.	"internationale demo-projecten" [B] "demo projecten opstarten" [D] "testplant/demo belangrijk in wegnemen onzekerheid bij investeerders" [F]
Business case improvement	Exploiting valuable by-products of gasification process such as biogenic CO2 and biochar for the improvement of gasification business case	"Biomassa biedt optie tot productie van biogene CO2" [D] "Nederland leent zich voor extra business case vanuit syngas (groengas)" [E] "tweestaps vergassing biedt extra business case uit de char" [E] "biogene CO2 en andere bijproducten kunnen onze business case versterken." [H]
Torrefaction - to improve business case	Torrefaction can improve the business case of biomass-to-syngas projects by increasing security of supply and lowering feedstock costs through upgrading low-value residual feedstock streams to usable feedstock streams for gasification.	"Torrefactie laagwaardige biomassa" [A] "Focus laagwaardige biomassa (torrefactie)" [H][B] "opwaarderen laagwaardige reststromen en diversificering feedstock supply" [F][H]
	Torrefaction can decrease logistic costs	"Logistieke voordelen torrefactie" [A][D] "Transport Voordelen" [C] "logistieke voordelen en CO2 reductie in transport" [E] "optimalisatie logistieke keten" [F] "verbetert logistiek" [G]

Table 15: Market development solutions

D.1.2 Supply chain

Sub-theme	Solution	Interview term, quote or source
Strategic partnerships for market entry and security of supply	Forming strategic partnerships with larger companies which are already active in biomass (for instance: energy or pulp and paper) sectors to overcome challenges and ensure a secure feedstock supply for biomass-to-syngas projects.	"Juiste partner vinden" [A] "projecten opstarten in coöperatie met grote partijen die een stabiele zijstroom van biomassa kunnen verzekeren" [D] "Contracten met staatbosbeheer en biomassa leveranciers. of met grote handelaren in biomassa zoals Uniper." [D] "Praten met energie-markt/paper&pulp om te kijken of het mogelijk is een zijstroom van de woodchips te krijgen" [D] "Partnerships feedstock locaties" [F]
Network formation and coordination	Create incentives and a policy framework to stimulate network formation between agri-sector and industry to strengthen the feedstock supply chain	"Juiste partner vinden" [A] "Relaties opbouwen agri-sector"[E][F] "Betere netwerk coördinatie met boeren/feedstock producers" [H], [[LLS18]]
Torrefaction	Diversifying usable feedstock streams through torrefaction, thereby increasing security of supply by being less dependent on small group of suppliers	"opwaarderen laagwaardige reststromen en diversificering feedstock supply" [F][H]
	Improving logistics of biomass transport through torrefaction	"Logistieke voordelen torrefactie" [A][D] "Transport Voordelen" [C] "logistieke voordelen en CO2 reductie in transport" [E] "optimalisatie logistieke keten" [F] "verbetert logistiek" [G]
	Torrefaction technology essential for creating homogeneous and tradable commodities	"Torrefactie essentieel voor creëren van commodities" [C] "torrefactie homogeniseert eigenschappen biocoal" [D] "Uniformer materiaal en pellets die makkelijker te handelen zijn" [D]

Table 16: Supply chain solutions

D.1.3 Policy and Subsidy

Sub-theme	Solution	Interview term, quote or source
EU-wide policy for sustainable biomass usage in the chemical industry	Create EU-wide policy regarding biomass usage and sustainability goals specifically aimed at the chemical industry to push the sector towards sustainability	hogere push verduurzaming [B] grote drive vanuit klantenkant [D] Telefoon roodgloeiend sinds bijmengverplichtingen Duitsland [E] drivers vanuit klantenkant [F] Fitfor55 maakt onze business case [H] koolstof beprijzing chemische sector opvoeren [F] , [Strengers & Elzenga]
Risk-fund or Capital subsidy	A subsidy scheme or risk-fund should be enlisted which aims to cover the investment risk of torrefaction and/or gasification projects through (partly) covering the capital expenses of a project.	"technologische onzekerheid kan worden afgedekt dmv subsidie" [D] "doorpak subsidie niet gericht op verdere ontwikkeling van de technologie op kleinschalig niveau maar op het afdekken van het investeringsrisico op grootschalige projecten is nodig." [D] "industrie-politiek: risico fonds gericht op dekken investeringsrisico op commerciële schaal benodigd" [E] "Overheid Kapitaalinvesteringen via instanties als InvestNL zou helpen in projectontwikkeling" [H]

Table 17: Policy and subsidy solutions

D.1.4 Law and regulation

Sub-theme	Solution	Interview term, quote or source
Promoting uniformity in biomass regulations	EU-wide uniform law- and regulation regarding sustainable biomass usage, standardisation and certificates	"Stimuleren uniformiteit wet-en regelgeving" [A] "meer internationale standaard op biomassa zetten" [B] "Biomassa te brede term geworden" [F]
Enhanced regulations for carbon tax and blending obligations in chemical industry	Stricter rules and regulations such as carbon tax and blending obligations specifically aimed at the chemical industry	"Duidelijke en strengere wet-en regelgeving" [B] "koolstof beprijzing chemische sector opvoeren" [F]

Table 18: Law & regulations solutions

D.1.5 Technology - solutions

Sub-theme	**Solution**	**Interview term, quote or source**
Knowledge development	Knowledge institutions play a vital role in researching and experimenting with technologies to increase their TRL and attract/convince companies to invest.	"onderzoekers hebben een belangrijke rol" [B]
	Demo-plants are essential for knowledge development regarding up-scaling of technologies	"internationale demo-projecten belangrijk voor kennis" [B] "demo projecten opstarten" [D] "test-plant/demo belangrijk in wegnemen onzekerheid" [F]
Process optimalisation	Modular design of torrefaction and gasification reactors to circumvent lack of knowledge and issues regarding upscaling	"modulair ontwerp" [E][F],
Torrefaction	Torrefaction improves gasification characteristics of feedstock and with that allows for better reaction kinetics and higher/cleaner syngas yields	"torrefactie homogeniseert eigenschappen bio-coal" [D] "torrefactie verbeterd gasificatie eigenschappen biomassa" [E]

Table 19: Technology solutions

E Questionnaire

In the section underneath a short description is given of the questions that were asked in the questionnaire, together with an overview of the answers that were received. The outcomes of this survey served as input for the prioritisation of barriers and the development of solutions.

E.1 Questionnaire set-up

In the document below 38 barriers to the implementation of the biomass to syngas value chain in the Netherlands are shown together with barriers for the implementation of torrefaction technology in this value chain. These barriers are derived from scientific- and grey literature, and from stakeholder interviews with actors in the value chain.

Question 1: Based on your expertise and knowledge, do you believe there are any significant barriers that were not discussed in the previous section, but play a crucial role in the development of the biomass-to-syngas value chain in the Netherlands? If so, please elaborate on these barriers and how they may impact the chain.

Question 2: Considering the barriers that were described in the previous section regarding the development of biomass-to-syngas value chain, please rate these barriers on their significance in terms of their potential to block the development of the biomass-to-X value chain below.

5 point Likert scale: Not significant at all - Extremely significant

Question 3: Please rate the following barriers on their significance to block the development and integration of torrefaction technology in the biomass-to-syngas value chain below.

5 point Likert scale: Not significant at all - Extremely significant

In the file below 18 solutions, derived from stakeholder interviews and literature, are shown for overcoming barriers and setting up the biomass-to-X value chain.
Question 4: In light of the barriers and solutions discussed in the previous section, what additional solutions or nuanced perspectives would you propose for setting up a biomass-to-syngas value chain in the Netherlands?

Question 5: Below eight theses are shown regarding the potential impact torrefaction can have on setting up a biomass-to-X value chain. Please fill in your level of agreement with these statements.

5 point Likert scale: strongly disagree - strongly agree

E.2 Results

E.2.1 Barriers added by stakeholders

In the survey stakeholders added only two additional barriers to the development of the biomass-to-syngas value chain.

- **Investment dynamics (increasing prices):** Investors and/or feedstock producers make use of the lack of natural and financial resources in negotiations with small scale torrefaction/gasification plants. Due to the heavy dependency of the small scale plants on a small group of investors and feedstock suppliers, there is a principal agent problem in which investors/feedstock suppliers can drive up their prices or equity demands.

- **Permitting and nitrogen deposition issues:** The current Nitrogen deposition issues in the Netherlands lead to long/and slow permitting schemes and a stop on many projects including sustainable projects.

E.2.2 Prioritisation of barriers to the development of biomass-to-syngas value chain

Thirty-five barriers to the development of a biomass-to-syngas value chain were presented to stakeholders. Barriers were deemed significant if they scored equal or above 3.50 (moderately-very significant), with a sub one standard deviation. Based on these selection criteria the following 12 barriers were selected as significantly blocking the adoption and implementation of torrefaction technology in the biomass-to-syngas value chain.

#	Barrier	Type of barriers (TIS & Influencing condition)
1	The term 'biomass' is too broad and does not distinguish between (sustainable) different biomass-feedstock streams.	Innovation specific institutions & Knowledge and awareness of technology
2	Subsidies do not properly cover the investment risks of gasification projects and do not support the development of commercial large-scale projects.	Innovation specific institutions & Natural, human and financial resources
3	There is high political uncertainty surrounding the use of biomass due to a strongly polarised public debate. Resulting in limited policy attention regarding the development of biomass-to-x technologies	Network formation and coordination & Socio-cultural aspects
4	Due to low policy attention there are no certification and subsidy schemes that focus on bio-genic syngas production	Innovation specific institutions & macro-economic and strategic aspects
5	Limited flexibility of gasification technology to handle diverse feedstock, limiting them to specific types and ratios, resulting in reliance on suppliers and hindered adaptability to supply chain fluctuations or uncertainties.	Production system & Knowledge and awareness of technology
6	Current policy schemes insufficiently connect to the cascading principle and therefore do not advocate for the up-cycling of biomass/waste streams	Innovation specific institutions & Knowledge and awareness of application and market
7	There is a lack of both EU and NL long-term policy specifically aimed at the chemical sector for making the sector more sustainable	Innovation specific institutions & macro-economic and strategic aspects
8	The high investment costs combined with high technological risk make investors hesitant to invest in biomass-to-x projects	Production system & Natural, human and financial resources
9	Limited ability to secure reliable feedstock supply of consistent quality due to limited availability and heterogeneity of the feedstock	Production performance and quality & Natural, human and financial resources
10	There is a lack of awareness and limited widespread knowledge regarding gasification technology among industry, institutions, local bodies, consumers, and entrepreneurs. Hindering the further commercial exploitation of biomass applications ultimately leading to market failures	Network formation and coordination & Knowledge and awareness of application and market
11	Political debate regarding the sustainability of biomass and NOx emissions has led to uncertainty regarding the future of biomass projects, making businesses and investors hesitant to invest in new projects, therefore leading to a lack of investments in the BtX industry	Network formation and coordination & Socio-cultural aspects
12	There is limited technical ability, knowledge, and personnel to develop gasification and torrefaction technologies and produce high-quality syngas	Network formation and coordination & Natural, human and financial resources

Table 20: Prioritisation barriers to value chain development stakeholders from survey

E.2.3 Barriers to the implementation and adoption of torrefaction technology

Nine barriers to the implementation and adoption of torrefaction technology into the biomass-to-syngas value were presented to participants. Barriers were deemed significant if they scored above 3.00 (moderately significant), with a sub one standard deviation. Based on these selection criteria the following 4 barriers selected as potentially blocking the adoption and implementation of torrefaction technology in the biomass-to-syngas value chain.

#	Barrier	Type of barriers (TIS & Influencing condition)
1	Process interruptions occur frequently due to technical challenges in achieving constant and well-controlled process conditions for the production of a uniform product	Production system & Knowledge and awareness of technology
2	Lack of knowledge regarding upscaling the technology	Production system & Knowledge and awareness of technology
3	The content of inorganic compounds in ash increases during torrefaction, which limits the utilization of torrefied biomass in gasification and combustion practices	Production system & Knowledge and awareness of technology

Table 21: Prioritisation barriers torrefaction technology development and implementation

E.2.4 Additional solution proposals

In the survey stakeholders added the following three solution areas.

- **Specific REDII related subsidies):** Compose subsidies in the Netherlands that relate to REDII, such as, Renewable Energy Premiums and Investment Grants aimed at the biomass-to-syngas value chain.
- **Separate permit procedures for green initiatives:** Create separate permit procedures for sustainable projects/initiatives that circumvent the nitrogen deposition issue in the Netherlands.
- **Active investment opportunities from government (like invest NL)**

E.2.5 Q5 -potential impact torrefaction

8 Theses were given regarding the potential impact of torrefaction technology on the biomass-to-syngas value chain. A thesis was deemed representable for stakeholder perspectives if it scored 4.00 (agree) or higher on average and if it had a sub-one standard deviation. Based on these selection criteria the following five thesis were selected as representative perceptions which stakeholders have towards the potential impact of torrefaction on the biomass-to-syngas value chain.

#	Thesis
1	Torrefaction can save logistics costs and improve the biomass supply chain, especially when investing in decentralized hubs.
2	Torrefaction can up-cycle low value waste streams thereby improving the business case of gasification projects because of lower feedstock costs, availability of a wider range of feedstock supply and less dependency on a limited group of feedstock suppliers.
3	Torrefaction is an essential technology for the successful development of a biomass-to-syngas value chain
4	Torrefaction provides a method of generating tradable commodities and therefore is essential for the future large-scale bio-based economy
5	Torrefaction improves the gasification characteristics of biomass and with that the feasibility of gasification projects

Table 22: Thesis regarding role torrefaction technology

F Webinar

This section contains the transcript and analysis of the webinar. The analysis followed an interpretive approach inspired by Bakker et al., as discussed in section 3.4.3, where the key topics and findings discussed by each expert from the transcript are summarised and used to form a narrative.

F.1 Transcript panel discussion

Name	**Expertise**	**Organisation & profession**	**Function in value chain**
Sander Peeters	Sustainable raw materials and fuels, sustainable industry	Advisor sustainability at RVO	Subsidy- & policy
Robin Post van der Burg	Torrefaction & gasification technology	Torrgas - CEO & owner	Technology development
John Bouterse	Business consulting across the entire value chain	Twinnovate - CEO	Consultancy

Table 23: Members of the discussion panel and their expertise

Statement 1 - Policy:

> *"Om de verduurzaming van de chemische industrie te bevorderen, is samenhangend overheidsbeleid nodig dat gebaseerd is op breed gedragen kennis over gasificatie-technologie en duurzaam biomassa gebruik. Daarnaast moeten beleidsmakers, industrie en wetenschap samenwerken om politieke consensus te bereiken over het gebruik van biomassa als duurzame grondstof."*

[Sander] Mee eens, maar niet volledig mee eens deels ook afhankelijk van de prijs en conurrentie met fossiele grondstoffen **[1]**. En op die wijze kiest de markt toch wel voor die fossiele grondstoffen aangezien die toch goedkoper zijn. Daarnaast is het ook zo dat de overheid inderdaad weinig kleur heeft bekend op dit gebied **[2]**, sinds eind April gelden dan wel bijmenverplichtingen in de industrie maar daarin zijn ook geen duidelijke invullingen van hoeveel daaruit daadwerkelijk uit biomassa moet gaan komen.

[Robin] Ik sluit mij aan bij deze stelling. Wel moet de nadruk meer liggen op gebruik van lignucellulose gebruik. Ook is het de vraag of breedgedragen kennis omtrent gasificatie-technologie en duurzaam biomassa gebruik goed over de buhne kan krijgen. Het is een heel complex begrip bijvoorbeeld. Bijvoorbeeld het probleem van crop-burning is helemaal niet bekend in Nederland wat, evenveel uitstoot opleverd als de gehele scheep- en luchtvaart wereldwijd. Zoiets alleen al uitleggen is al heel lastig dus denk dat het uitleggen van de gasificatie-technologie niet perse je doel moet zijn maar dat je het terug moet brengen naar de basis, -> dat de bouwstenen van de chemie, schaalbaar en groen dmv biomassa kunnen worden gesynthetiseerd. Als je dat over de buhne krijgt dan ben je al goed opweg en dus niet inzoomen op de technologiën.

[John] Ik sluit mij aan bij deze stelling, platform biomassa feiten is ook opgericht met de reden om breedgedragen kennis te ontwikkelen en consensus te krijgen omtrent biomassa gebruik. Ik denk wel dat je stelling zo te moeilijk geformuleerd is, want de politiek laat zich sturen door de consument. Dus ik vind dat de consument ook tot deze stelling behoort en dat je dus de maatschappij moet overtuigen dat biomassa duurzaam kan worden toegepast en de gevaren van die crop-burning bijvoorbeeld.

[Myself] er is een kleine groep deelnemers die volledig mee oneens gestemd heeft, dus ik zou deze deelnemers uit willen nodigen om dit toe te lichten.

[Audience member] Kan me voorstellen dat de mensen die 'volledig mee oneens' hebben ingevuld het idee van de 'triple helix' te ingewikkeld vinden en stellen dat het ook onderling tussen techneuten geregeld zou kunnen worden en daarom de weg die in de stelling staat omschreven te lang vinden. Zelf heb ik volledig mee eens gestemd overigens.

Statement 2 - Laws and regulation

> *"Uniforme wet- en regelgeving en een internationale standaard op duurzame biomassa zijn nodig om de verhandelbaarheid te vergroten en de complexiteit van het opzetten van een duurzame biomassa naar syngas waardeketen te verminderen."*

[John] Je probleemstelling is anders dan je vraagstelling, ik denk namelijk niet dat er een overvloed aan regelgeving en certificering is op biomassa. En het tweede was, biomassa is een te brede term. Het is wel zo dat voor biomassa veel meer regels gelden die niet voor fossiel gelden en dat zou gelijk moeten worden getrokken. En dat biomassa een te breed begrip is, is alleen omdat biomassa een vies woord is geworden in Nederland en dat er alleen maar wordt gefocust op biomassa stromen voor energie centrales terwijl er zo veel andere soorten biomassa stromen zijn die gebruikt kunnen worden, bijvoorbeeld uit de agri-sector. De verhandelbaarheid neemt alleen maar toe op het moment dat er uniforme wet-en regelgeving is en standaardisering dus daar ben ik het wel met je eens, maar ik zou niet zeggen dat de wet-en regelgeving momenteel een belemmering is.

[Robin] Ik denk dat het essentieel is dat er commoditising plaatsvindt in de biomassa en daar bedoel mee dat we gaan naar gestandaardiseerde energie-dragers/grondstoffen, en dat hebben we alleen voor witte-houtpellets momenteel. Eigenlijk moeten we als industrie overstappen op getorreficeerd materiaal om zo diverse feedstock stromen te homogeniseren en daarmee een gestandaardiseerd product maken waardoor je niet meer over al die verschillende soorten biomassa praat en je die stromen dus weet te commoditiseren. En de term biomassa is eigenlijk een container begrip wat nergens op slaat, wij technici praten zelf over lignucellulose, dus alle niet eetbare biomassa. En als je bijvoorbeeld een korrel graan maakt dan is 80% ligunucellulosic waste en eten gaat dus juist in synergy met eten en niet voedsel vs. energy. Dat moet men inzien, dat biomassa duurzaam beschikbaar is en geproduceerd kan worden. En dus die commoditising, waarbij dat conversie proces in het begin van de keten essentieel is.

[Sander] Ik kan me daar volledig bij aansluiten, ik had volledig mee eens aangegeven. Aan de ene kant hebben we wet-en regelgeving nodig om die duurzame biomassa stromen te garanderen. Ik pleit zelf wel voor een meer uniforme wet-en regelgeving want wat we op dit moment zien is dat elk land zijn eigen duurzaamheidsregels gaat opstellen en dat die keten verstoord. Dus ik pleit zeker voor een meer internationale wet- en regelgeving.

[Audience member 1] Ik wil hier nog aan toevoegen dat in de RED natuurlijk een groot deel van afgedekt is + dat standaarden en schema's elkaar moeten gaan erkennen. Alleen is dat nog niet zo ver, dus ik denk dat daar wel een grote stap in gezet is met de RED. Daarnaast hoorde ik torrefied materiaal voorbij komen, ik werk al 15 jaar in de industrie en volgens mij is torrefactie nog nooit grootschalig gelukt dus ik zie het zeker graag tegemoet.

[Audience member 2] Ja ik zit te denken aan de term **groene koolstof** net als groene waterstof.
[Robin] Daar ben ik het volledig mee eens. Daarnaast is het essentieel dat we gaan inzien dat we die koolstof nodig hebben, de lobby van waterstof is daar erg sterk in dat te voorkomen. Maar dat we die koolstoffen nodig als we duurzame chemicalieën en biobrandstoffen willen en dat we er dus niet gaan komen met alleen waterstof.

Statement 3 - Lack of investments

> *"Investeren in pilot-plants is essentieel voor de kennisontwikkeling omtrent opschaling van de technologieën en het overtuigen van investeerders. Het vinden van betrouwbare partners vanuit de energie-sector om zo lange termijn feedstock-contracten te verzekeren is daarbij essentieel."*

[Sander] Ja ik heb hier zoals velen Neutraal op gestemd. Met de reden dat de bekende spelers wel bekend zijn met vergassingstechnologie en methaniseren etc. En in mijn ogen is het niet zo zeer een technologisch probleem, eerder een econmisch probleem waarbij fossiele grondstoffen toch relatief goedkoper zijn dan biomassa en het conditioneren ervan. En de industrie dus bij fossiel blijft, dus zolang dat verschil niet gestimuleerd wordt en er blijft zie ik de projecten niet van de grond komen. Want de rest is best wel te organiseren.

[Robin] Sluit eigenlijk aan bij wat ik aangaf, je moet commoditisen, waarbij je niet de ene dag stro gaat gebruiken en de andere dag B-hout. En ten tweede, je moet grootschalig, je wilt niet kleinschalig gaan vergassen en een van de moeilijke dingen daarbij is dat er twee verschillende soorten vergassers zijn. Vergassers voor de energie en vergassers voor syngas productie die volledig teervrij syngas dienen te maken, en die tweede soort vergasser is vele male complexer. En de bestaande vergassers zijn allemaal ingericht op kolen en niet op biomassa. En biomassa heeft de problematiek van mineralen. Als je biomassa vergast sluit je die mineralen ook in en verbreek je dus die mineralen kringloop dus als je met zo'n originele vergassingstechnologie werkt dan sluit je die mineralen dus in je slack wat geen duurzame oplossing is. Dus daarin is het essentieel dat je een vergassingtechnologie toepast die, die mineralen niet verbrand of insluit in slack maar omzet in actieve biochar en dus een waardevolle reststroom creëert. Biochar is op dit moment dan ook het hoogst betaalde voluntary CO2 recht ter wereld, dus dit geeft echt de duurzaamheid van dit product aan. Ik vind het daarom heel belangrijk om te stellen dat vergassingstechnologie niet over 1 kam gescheerd kan worden daar zitten echt hele grote nuance verschillen in hoe je dat doet.

[John] Ik ben het niet mee eens dat betrouwbare partners vanuit de energie-sector moeten komen. Ik denk dat ze die kans gehad om die keten op te zetten en zo te koppelen aan de chemische industrie. Want de chemie is alleen maar gebaat bij verschillende soorten biomassa stromen en grote volumes waaruit ze betrouwbare levering feedstock kunnen verzekeren, en die supply chain is er nu nog niet. Dat moet nu nog opgezet gaan worden en ik denk zolang die supply chain er niet is het een uitdaging voor de industrie wordt om over te schakelen van fossiel op duurzame feedstock stromen. Dus je kan die pilot-plants wel doen maar je moet die schaal inderdaad creëeren. En ik denk dat torrefactie daarin wel een oplossing is maar ik denk vooral dat we moeten kijken naar extra spelers voor het leveren van die feedstock en dan niet uit de energie maar bijvoorbeeld uit agri-bedrijven die dit nu als side-business model kunnen gaan gebruiken.

[Audience member] Ik ben wel benieuwd hoe men aankijkt tegen, los van investeringen in pilot-plants, investeringen in het algemeen, wordt er eigenlijk uberhaupt wel genoeg geïnvesteerd in deze complexe technologie? en hoe overtuigen we investeerders om die invesering dan wel te gaan doen?

[Robin] Ja dat is een hele lastige, dat is het kip-ei probleem waar je mee zit. Wij hebben onze eerste licensie verkocht aan gasunie voor SNG , wat natuurlijk een rare route is maar dat ter zijde. En dan zien we dat we in weze heel goed zijn als Nederland zijnde in Innovatie er zit veel kennis bij kennis instituten om die technologie naar TRL 7 te brengen zeg maar, maar als je eenmaal bij TRL 7 en je wilt naar TRL 8 of verder dan is dat ongelooflijk moeilijk. Er is heel weinig geld beschikbaar in de markt om die investeringen te doen.

Statement 4 - Subsidy

> *"Publiek private samenwerkingen zijn essentieel voor de ontwikkeling van de waardeketen. De overheid dient actieve investeringsmogelijkheden zoals InvestNL meer beschikbaar stellen aan bio-based chemie om zo investeringsrisico's af te dekken."*

[John] Ik heb heel snel op helemaal mee eens gedrukt want ik vind dat de overheid daar inderdaad een te passieve rol in aanneemt. En dat je met een commerciële installatie of het naar TRL 9 brengen van je innovatie inderdaad niet compatibel bent met de huidige subsidie regelingen. Als je ziet wat de doorlooptijden zijn dan praat je soms wel over een aantal jaren terwijl je soms pas 3 maanden van te voren te horen krijgt wanneer een subsidie opening plaatsvindt. En daarin zou ik pleiten voor een combinatie van CAPEX en OPEX subsidies waarin je veel meer richt op CAPEX in die beginfase van de projecten voor het stimuleren van die ontwikkeling en dat je de OPEX om die eerste paar jaar van operatie te dekken. En dat is er nu helemaal niet. En de initiatieven van de overheid zoals InvestNL zijn daarin goed, echter is het een zeer complexe organisatie waarin je eigenlijk eerst door alle andere financieringsmogelijkheden moet zijn afgewezen voordat je daar aan bod komt.

[Robin] Ik sluit me helemaal aan bij wat John zegt op het schuld gedeelte vanuit de banken komt geen enkele dekking en daar zou de overheid dekking in geven. Als je maar een (risico)fonds hebt wat dekking geeft op die financieringsrisico's. En daarnaast hoorde ik dat er voor waterstof wel zo'n fonds bestaat maar niet voor groengas, puur door die zware lobby die achter waterstof zit. Als je zorgt dat er dekking op leningen gegeven kan worden, dan breng je die projecten op gang. En dat is denk ik één van de grootste dingen die nu mist, gewoon dat die zekerheid gegeven kan worden die de banken nu niet kunnen verlenen in dit stadium.

[Sander] Ik kan daar ook zeker in meegaan. Wat we zelf heel erg horen is dat banken heel erg afwezig zijn of afhaken bij het horen van het woord biomassa. En daarvoor is InvestNL in het leven geroepen om bij dit soort investeringen wel in te springen, maar dan moet je inderdaad wel een bepaalde grootte aan investeringen hebben. Zelf zie ik wel kansen dat de projecten van de grond zouden kunnen komen op het moment dat je inderdaad die keten kunt gaan sluiten, dus het aanttrekken van die grote investeerders. En dan moet je ook nog die stikstofknelpunten zie te parreren zegmaar. Dus we zitten wel in een heel lastig traject. Als je kijkt naar de subsidies bijvoorbeeld daar passen die grotere projecten dan inderdaad niet in en dan zou de combinatie van een CAPEX en OPEX subsidie die wordt nog wel meer genoemd dus dat zou wel een oplossing kunnen zijn. En wat ook vaak wordt gezegd, Nederland heeft niet zo veel biomassa. Die leverings contracten moeten dan wel zeker gesteld zijn en dat weegt dan wel mee in het verkrijgen van investeringen.

[Robin] Ik vind het leuk dat je dat zegt over die import van biomassa want dat is zo een slecht argument. In Nederland importeren we vrijwel alles, onze cacao en aardolie wordt bijvoorbeeld ook geimporteerd. Dus ik snap echt niet waarom er elke keer zo moeilijk gedaan wordt in Nederland over het importeren van biomassa commodities. En dat wordt niet gedaan op basis van feiten maar op bepaalde sentimenten en lobby dat er zo'n absurde houding tegenover het importeren van biomassa commodities is onstaan.

[Sander] Ja dat klopt helemaal Robin dat komt inderdaad door dat sentiment wat er heerst. Anderzijds zijn we bijvoorbeeld wel een heel groot importeur van soja bijvoorbeeld maar dat wordt dan weer niet gezien als een probleem. Maar wat ik probeer te zeggen is dat we daar wel mee te dealen hebben en dat is een lastig probleem. Maar wat ik probeer te zeggen dat er wel gevallen zijn van torrefactie of gasificatie projecten waar subsidie aan verleent is maar waar die lange termijn contracten toch uitblijven en de projecten faalden.

[Robin] Ja dat is ook zo, dat is ook het kip-ei probleem wat Tom terecht aangaf dat is ook heel slecht voor de ontwikkeling van de keten dat dit vroeger gebeurd is. Dus je moet echt Vertically integrated hiernaar kijken. En ik denk dat de markt/keten enorm opgang komt zodra die gasificatie installaties, met enige vorm van overheids-steun staan. En ik heb genoeg biomassa leveranciers over de wereld gesproken om te weten dat er genoeg biomassa beschikbaar is voor deze projecten, dus zo lang die projecten maar gebouwd worden kan de keten gesloten worden.

Statement 5 - Torrefaction

> *"Torrefactie-technologie kan worden gebruikt voor het opwaarderen van laagwaardige biomassa stromen en verbetering van de gasificatie eigenschappen van feedstock en vormt daarmee een essentiële technologie voor het opzetten van een duurzame en rendabele biomassa naar syngas waardeketen."*

[Sander] Ik ben het er helemaal mee eens. De vraag is eerder want we willen natuurlijk naar een homogene grondstof toe om die gasificatie eigenschappen te verbeteren en die syngas verontreinigingen te verminderen. De vraag is ook wil je die torrefactie Unit ook in Nederland plaatsen of wil je die bij de bron plaatsen?

[Robin] Ja daar kan ik meteen op antwoorden, uiteraard moet je naar de biomassa toe met de torrefactie unit om zo die logistieke keten het best te optimaliseren. Om een idee te geven als je lignucellulosic biomass gaat torrificeren dan verhoog je de energie-dichtheid van die biomassa een factor 30-40, dus van 30-40 kuub stro kan je ongeveer 1 kuub getorreficeerde pellets maken. De winst in logistiek is dus enorm gezien het gewichtsverlies en de betere opslag eigenschappen die je gecreëerd hebt. Dus je moet echt naar de biomassa toe, waarbij het essentieel is dat je technologie is aangepast aan de schaalgrootte van de afname locatie. Dus het is essentieel om naar de bron toe te gaan.

[Jonh] Ja ik sluit me bij beide aan. Alleen heb je daar bij laagwaardige stromen meer moeilijheden in gezien het feit dat dit in kleine hoeveelheden op verschillende plekken beschikbaar komt, waarin de infrastructuur een belangrijke factoor is. Maar torrefactie is zeker van belang om van verschillende soorten biomassa een grondstof te kunnen maken om daarmee de sector te kunnen bedienen.

F.2 Webinar analysis

In the sections below the nuances, barriers and solutions which stem from the webinar are summarised in combination with the outcomes of the live polling. Overall, most statements show a high level of agreement, but not full agreement, in most cases the audience or panel therefore added valuable nuances to the presented solutions and barriers. No new barriers or solutions were introduced during the discussion, however some barriers and solutions were specifically emphasised by the panel-experts, these are included in the table below. The outcomes of this webinar will be used for analysis in the expert reflection session on the identified barriers and solution proposals of this research (see 3.4.3)

F.2.1 Nuance and Summary of standpoints

F.2.1.1 Statement 1:

[Outcome voting] 27% fully agrees ; 54% agrees ; 8% neutral; 0% disagrees; 12% totally disagrees

Sander Agrees, but notes that since fossil-based chemicals are still cheaper than bio-based chemicals, lack of sustainability of chemical sector is not all down lacking policy. However, he admits that the government has been slow in policy formation and even now is still ambiguous over the role of biomass in their policy.

Robin Agrees with the statement, however he questions if the focus should be on creating widespread knowledge regarding gasification technology and sustainable biomass usage specifically and advocates that simply convincing the general public that the building blocks of chemistry can be synthesized scalable and green using biomass should be the main goal.

John Agrees with the statement as well, however joins Robin in saying that creating widespread knowledge regarding biomass gasification is too complex and adds that the focus should be on convincing the consumer/general public of the sustainability of biomass.

Audience member Potential reason for not agreeing with the statement is that some people might find the 'triple helix' approach sketched in the statement too complicated and lengthy. They might argue that the value chain could be set-up much faster if mutual agreement between technicians could be arranged.

F.2.1.2 Statement 2

Outcome voting: 19% fully agrees ; 57% agrees ; 10% neutral; 5% disagrees; 10% totally disagrees

John Does not necessarily believe there is an excess of regulations and certification. However highlights that many more rules apply to biomass that do not apply to fossil fuels and that should be equalised (suggests and unfair regulatory advantage towards fossil fuels). Moreover regarding the broad term 'biomass' he adds that mostly the negative stigma surrounding the term is detrimental, stemming from use in energy. Although, he doesn't believe law and regulation is currently a barrier, he does advocate for making uniform laws and regulations and standardization to increase the tradability of biomass.

Robin Emphasises the importance of commoditisation of biomass to standardised bio-based raw materials. Therefore he highlights that torrefaction has an essential role in the value chain fo creating these homogeneous standardised commodities from various feedstock streams. Once more he stresses that the emphasis should lie on convincing the industry that biomass is sustainably available.

Sander Fully agrees with the statement and advocates for making uniform international rules and regulations.

AM 1 Notes that by enlarge the new RED III regulation has covered the issue of over-certification by stating that standards and policy schemes have to acknowledge each other. Additionally he mentions he would like the integration of torrefaction technology in the value chain, but is sceptical about the development of the technology.

AM 2 & Robin AM2 proposes the term 'green carbon' as alternative to 'biomass. [Robin] Agrees, stating its essential that the industry/general public realises that renewable carbon is essential in the production of sustainable chemicals and fuels and the lobby behind hydrogen is effectively preventing the acknowledgement of the importance of renewable carbon as a sustainable resource.

F.2.1.3 Statement 3

Outcome voting: 14% fully agrees ; 29 % agrees ; 48% neutral; 0% disagrees; 10% totally disagrees

Sander Voted neutral, noting that the familiar players are well known will gasification technology. Further highlighting that he doesn't view there is a technological problem, but more an economical problem in which fossil resources are cheaper than biomass. Adding that as long as the cost difference is not financially supported (suggesting subsidy/governmental funding) the market will remain using fossil resources.

Robin Once again stresses the necessity of producing commodities. Further he highlights gasification should happen on large scale and not small scale, so he doesn't advocate demo-projects. Additionally, he stresses the differences in gasification methods and that the focus should be on preserving the minerals during gasification as they are highly valuable, an example he gives is the sustainability and financial gain of producing biochar.

John Does not agree, because he believes the partners shouldn't come from the energy sector but efforts should be put in network formation with the agri-cultural sector to provide biomass as a side-business. Furthermore he adds that the development of a reliable and diverse supply chain of scale is necessary for the industry to switch from fossil resources to sustainable feedstock streams. Additionally, torrefaction is proposed as a solution in helping to set-up this value but first and foremost, more players and feedstock should be attained in order to set-up successful projects.

Question AM *what is your view on investments in general in the technologies and convincing investors to make investments in your industry?*

Robin Stresses the problem of the mismatch between subsidy schemes and what is needed for the commercialisation of the technologies, stating there is to little money available in the market to make the necessary investments. Furthermore, he mentions the 'chicken and egg' problem as withholding investments, thereby connecting to John's previous statement.

F.2.1.4 Statement 4

Outcome voting: 47% fully agrees ; 42 % agrees ; 11% neutral; 0% disagrees; 0% totally disagrees

John Fully agrees, stating that the government is having a too passive role and there is a mismatch between current subsidy schemes and what is needed to bring the techolgies up to commercial scale or TRL 9. Further highlighting that the lead times of projects do not match the short notice in which projects are announced. He suggest a combination of CAPEX and OPEX subsidies which can cover both the short-term risk of high capital investments and the operational cost of the initial phase of operation. Additionally, he states that initiatives such as InvestNL are nice, but to complex to really deliver the necessary support.

Robin Agrees with John, further adding he thinks this is one of the biggest things that is missing right now. He adheres to the idea of the development of a risk-fund which covers the investment risk in the industry. Stating that cover on loans should be provided in order to give the security which banks can not provide in the initial stage of project development and get projects started.

Sander recognises the problem and views of Robin and John, adding that the current nitrogen deposition issues add in blocking investments into the development of new projects. He further agrees with the proposed solution of developing a combined CAPEX and OPEX subsidy.

Discussion Sander and Robin had an argument regarding the fact that there is not enough biomass available in the Netherlands and the negative stigma on importing biomass is partly preventing the build up of the value chain. Once again referring to the 'chicken and egg' problematic. Robin therefore states that he believes that the focus should be on the development of commercial gasification projects in the first place and once these are available, feedstock supply chain will follow.

F.2.1.5 Torrefaction

Outcome voting: 33% fully agrees ; 33 % agrees ; 33% neutral; 0% disagrees; 0% totally disagrees

Sander Fully agrees, stating the need of torrefaction technology for the production of homogeneous products which improve gasification characteristics and syngas production. However he question's whether torrefaction should be centrally developed in the Netherlands or decentralised near the feedstock source.

Robin agrees and answers Sander, by stating that torrefaction should be developed decentralised near the source to improve the logistics of the supply chain by reducing the mass, and improving the energy-density and storability of the feedstock. He emphasises decentralised development near the source and that torrefaction units are customised according to the location of feedstock production.

John Also agrees, adding that torrefaction is important in processing varying feedstock streams into homogeneous raw material for the industry. Furthermore he highlights that there is a logistical challenge regarding the use of low-value feedstock streams due to the small quantities and highly dispersed location in which it becomes available.