Dynamics of sustainable transport innovation: a case study of biofuels, hydrogen and LNG in the Dutch inland shipping sector

Coma-Cros, Nuria; Spekkink, Wouter; van Duin, Ron; Edelenbos, Jurian

Citation (APA)
Coma-Cros, N., Spekkink, W., van Duin, R., & Edelenbos, J. (2025). Dynamics of sustainable transport innovation: a case study of biofuels, hydrogen and LNG in the Dutch inland shipping sector. *Transportation Planning and Technology*, 1-28. https://doi.org/10.1080/03081060.2025.2591942
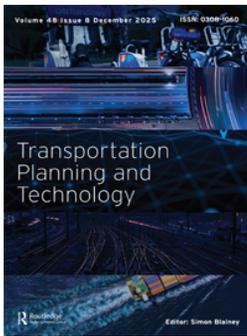
Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Dynamics of sustainable transport innovation: a case study of biofuels, hydrogen and LNG in the Dutch inland shipping sector

Núria Coma-Cros, Wouter Spekkink, Ron van Duin & Jurian Edelenbos

View supplementary material ⧉

Published online: 10 Dec 2025.

Submit your article to this journal ⧉

Article views: 144

View related articles ⧉

View Crossmark data ⧉

Routledge
Taylor & Francis Group

Dynamics of sustainable transport innovation: a case study of biofuels, hydrogen and LNG in the Dutch inland shipping sector

Núria Coma-Cros [a], Wouter Spekkink [a], Ron van Duin [b,c] and Jurian Edelenbos [a]

aDepartment of Public Administration and Sociology, Erasmus University Rotterdam, The Netherlands; bFaculty of Technology, Policy & Management, Delft University of Technology, The Netherlands; cCenter of Expertise HRTech, Rotterdam University of Applied Sciences, The Netherlands

ABSTRACT

The Dutch inland shipping sector aims to nearly eliminate emissions by 2050 by transitioning away from fossil fuels. While alternative fuels are being developed, scaling them up remains challenging due to complex system dynamics, often leading to innovation failure. Existing studies identify scale-up factors but often overlook interactions between factors. This study examines the scale-up dynamics of biofuels, hydrogen and LNG. Scientific literature, news articles and interviews are analysed to construct causal loop diagrams depicting the main relationships between economic, technological, political and social factors. Six mechanisms showcasing scale-up dynamics are identified, highlighting the widespread impact of uncertainty – influenced by technical challenges, resource availability and fuel alternatives – and industry interest – influenced by cost–benefit assessment, technical challenges and resource availability. While biofuels, hydrogen and LNG show common mechanisms, resource availability creates key differences. A holistic approach addressing uncertainty and industry interest is needed to shift a system currently reinforcing fossil fuels.

Highlights

- Systems thinking and innovation theories are used to present factors and mechanisms that contribute to the scale-up (or lack thereof) of three alternative fuels: biofuels, hydrogen, and LNG.
- A six-step methodology, based on content analysis, transforms data from 33 scientific articles, 180 news articles and 12 expert interviews into causal loop diagrams that illustrate scale-up dynamics.
- Six underlying mechanisms, made up of feedback loops connecting multiple factors, highlight the widespread impact of uncertainty – influenced by technical challenges,

CONTACT Núria Coma-Cros ✉ comacrosespejo@essb.eur.nl 🏛 Department of Public Administration and Sociology, Erasmus University Rotterdam, Burgemeester Oudlaan 50, 3062 PA Rotterdam, The Netherlands
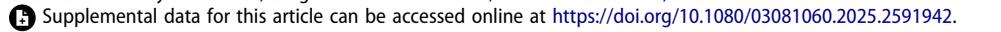
ⓘ Supplemental data for this article can be accessed online at https://doi.org/10.1080/03081060.2025.2591942.

resource availability and fuel alternatives – and industry interest – influenced by cost–benefit assessment, technical challenges and resource availability.
- Perceived potentially abundant resources for hydrogen and LNG support their scale-up, while limited resources for biofuels reduce competitiveness and create uncertainty, hindering their scale-up.
- A holistic approach addressing uncertainty and industry interest is needed to scale-up alternative fuels and shift the existing system currently reinforcing the use of fossil fuels.

1. Introduction

Inland shipping plays an important role in transporting goods in Europe, where 41,000km of waterways connect hundreds of cities and industrial areas across 13 countries (European Commission [EC], 2021). Inland vessels move these goods through inland waterways, often crossing national borders to load and unload their products in inland ports and seaports (Roso et al., 2020). By transporting dry bulk, liquid bulk and containers, inland shipping contributes to the competitiveness of other economic sectors (e.g. the construction sector), and seaports (e.g. the port of Rotterdam) (Wiegmans & Konings, 2017). The importance of inland shipping in Europe is expected to grow further; the EC (2020) prioritises inland shipping over other transport modes and calls for 75% of road-transported goods to be transported by inland waterways or rail. Additionally, a 50% increase in freight transport by 2050 is projected (EC, 2023).

Preference for inland shipping is often attributed to its many advantages, including safety, low costs, the unused carrying capacity of waterways and, especially, its relatively clean transport per transported tonne (Fan et al., 2021; Roso et al., 2020). The high carrying capacity of inland vessels allows for relatively low fuel consumption per tonne-km of transported goods. Inland shipping consumes 17% less energy per tonne-km than road transport and 50% less than rail transport (EC, 2021). Nonetheless, the environmental impact of inland shipping is significantly compromised by the fact that 95% of inland vessels are still powered by fossil fuels (Fan et al., 2021). Thus, if the EU is to meet its obligations under the Paris Agreement, significant efforts need to be made to change the energy source of inland vessels. It is also commonly argued that the sustainability performance of inland shipping is lagging that of road transport (Hekkenberg & Liu, 2017; Roso et al., 2020). If this trend continues, road transport could become more sustainable than inland shipping, making inland shipping less advantageous and hampering modal shift ambitions (Verberght, 2020).

The Netherlands is the largest contributor to inland shipping in Europe (Eurostat, 2024). Thus, it plays a key role in reducing emissions. In 2021, inland shipping accounted for 33% of transported goods by tonne-km in the country (Kennisinstituut voor Mobiliteitsbeleid, 2021). Actors in the sector have agreed to reduce 95% of emissions by 2050 in a shift towards zero emissions (ZE). This was formalised with the Green Deal (2019), a non-legally binding agreement signed by several parties, including Ministries, provincial authorities, trade associations, ports, banks and research institutes. The shift towards ZE requires an energy transition involving the adoption of new fuels (e.g. hydrogen, biofuels), energy sources (e.g. solar power) and propulsion methods (e.g. fuel cells). However, such innovations are difficult to implement, as they require changes in

various elements within and beyond the sector (Calderón-Rivera et al., 2024; Verberght, 2020), including infrastructure, vehicles, services (Wee et al., 2022), public policies and cultural behaviour (Geels, 2004). Previous research has generated insights in the factors that influence the scale-up of transport and inland shipping innovations, such as industry interest, a positive business case, technological readiness, environmental benefits, infrastructure compatibility and regulatory compliance (Feitelson & Salomon, 2004; Hekkenberg & Liu, 2017; Linzenich et al., 2023; Maraš, 2017; Verberght, 2020; Wee et al., 2022). However, there is still a limited understanding of the complex dynamics through which these factors interact (Hou & Geerlings, 2016; Pel et al., 2022).

This study investigates the dynamics influencing the scale-up of alternative and more sustainable fuels in the Dutch inland shipping sector. This refers to all vessels navigating on Dutch inland waterways, regardless of their flag, since they are all affected by factors such as infrastructure, legislation, or fuel prices. The starting point is that these dynamics are generated by causal relationships between factors (Sterman, 2002). Factors can refer to anything that increases or decreases in value (e.g., industry interest). A causal relationship between factors exists if the change in value of one factor leads to a change in value of another factor. This study explores how various political (e.g., laws), social (e.g., industry interest), technical (e.g., technological challenges), and organisational (e.g., collaboration) factors influence the scale-up of sustainable fuels, which is also a factor in itself. To understand their interactions in the broader system, this study identifies *mechanisms* – groups of factors interrelated in ways that regularly produce the same outcome (Hedström, 2005). These mechanisms can be used to illustrate recurring patterns that shape, in this case, the scale-up of sustainable fuels. In this study, mechanisms are represented as distinct segments of the dynamic interactions between factors. With the goal of mapping dynamics that influence the scale-up of sustainable transport and inland shipping innovations, this paper answers the following question: *What mechanisms explain the scale-up (or lack thereof) of alternative fuels in the* Duch *inland shipping sector?*

A qualitative approach is used to map out factors and mechanisms that contribute to the scale-up of biofuels, hydrogen, and liquefied natural gas (LNG). Data are drawn from news articles, scientific articles and expert interviews. The focal innovations were selected in the first research step. They were chosen because they are all alternative fuels applicable across various vessel types, unlike exchangeable battery containers, which are mainly used in container vessels. Moreover, their differing maturity levels offer insights from established patterns (e.g., LNG) as well as opportunities for guiding future interventions (e.g., hydrogen). The results are visualized in three Causal Loop Diagrams (CLDs) (Sterman, 2002) that enhance understanding of innovation dynamics in the energy transition of the sector. The findings of the CLDs are discussed at an aggregated level to explain the broader dynamics of alternative fuel scale-up in the sector, rather than examining the specifics of each individual fuel. This can become input for future quantitative simulation models and for scenario analyses that test the impact of interventions (Kirichek et al., 2023). These more advanced steps require the development of hypotheses about the functioning of the system (Lara et al., 2023), which is a key contribution of this paper.

The remainder of this paper is structured as follows: Section 2 discusses the theoretical approach of the study; Section 3 explains the methods employed, Section 4 reports the

results using CLDs; Section 5 includes discussion points; and Section 6 ends with conclusions.

2. A systems thinking approach to inland shipping innovation

2.1. Factors influencing inland shipping innovation

Transport innovations are defined as 'new elements of the transport system that are implemented in the real world' (Wee et al., 2022,1). The transport system is composed of infrastructure, vehicles, energy supply, and services (Wee et al., 2022), though broader definitions also include public policies, consumer behaviour, and social practices (Geels, 2004). Inland shipping has been shaped over time by key innovations, such as canals, steam-powered vessels, diesel engines and containerisation. Recent innovations often aim to reduce fuel costs, for example by enlarging vessels, as this is one of the few options of vessel operators to stay competitive (Hekkenberg & Liu, 2017). Since the early 2000s, there has also been considerable attention on improving the environmental performance of vessels (Hekkenberg & Liu, 2017). To achieve its zero-emission (ZE) ambitions, the sector requires innovations in alternative fuels and propulsion methods. Current ideas include new combustion fuels (e.g., biofuels, hydrogen, methanol, ammonia) and electrification of vessels using batteries and fuel cells. Researchers and experts in the field are actively discussing the potential to scaleup these innovations (see e.g. Bakker et al., 2022; CCNR, 2022; Linzenich et al., 2023).

The scale-up of transport innovations has proven to be difficult, with the majority of innovations failing (Filarski & Mom, 2008; Wee et al., 2022). The factors influencing the scale-up of alternative fuels in the inland shipping sector are multiple and diverse. Adopting alternative fuels requires costly vessel modifications or the construction of new vessels. These are high-risk options for small operators, who make up the majority of businesses in the sector (Hekkenberg & Liu, 2017). Thus, scholars and practitioners often focus on technical and economic challenges, such as the low technological readiness of alternative fuels and the insufficient economic incentives to adopt them (e.g. Karaarslan & Quispel, 2021; Perčić et al., 2021). Another key challenge that has received attention is the chicken-and-egg dilemma, which lies in deciding whether to invest first in the infrastructure for fuel supply or in the vessels that drive fuel demand (e.g. Yao et al., 2024). The scale-up of transport innovations is also affected by political, institutional, social and organisational factors, such as regulations, the public's perception of problems and societal support, although these factors are underexplored (Feitelson & Salomon, 2004; Hou & Geerlings, 2016). Notable exceptions include Verberght's (2020) doctoral thesis, which conceptualises innovation in inland shipping and examines factors within an institutional context, and Wiegmans and Konings' (2017) book, which identifies key drivers of sector competitiveness.

The multitude of factors influencing the scale-up of transport and inland shipping innovations is interconnected, requiring a combination of factors to scale-up (Verberght, 2020). For example, hydrogen's lower energy density requires more space onboard than diesel, reducing cargo capacity and profitability. Likewise, hydrogen's flammability requires new safety regulations and public acceptance. These interconnections indicate that change in one factor can lead to a cascade of changes in other factors, creating a

dynamic system that is continuously changing (Pel, 2022; Temenos et al., 2017). This can result in complex dynamics, where causes and effects are distant in time and space, and in trade-offs between different desired outcomes and between short-term and long-term effects (Sterman, 2002). Ignoring the interconnectedness of system-elements and their dynamics can result in simplified understanding and naive interventions that are therefore often ineffective and/or lead to unintended consequences. Table 1 presents a non-exhaustive overview of factors influencing the scale-up of transport and inland shipping innovations previously identified in the literature. However, transport studies tend to overlook innovation dynamics, favouring approaches based on incremental and controlled optimisation processes (Pel et al., 2022).

2.2. Systems thinking in inland shipping innovation

Scaling up inland shipping innovations requires understanding inland shipping as an interconnected system, where its performance is influenced by individual elements and the dynamic relationships between them (Calderón-Rivera et al., 2024). To capture the dynamic complexity of scaling up innovations in the inland shipping sector, this study builds on the Feitelson and Salomon (2004) framework while incorporating systems thinking (Forrester, 1994; Sterman, 2002). Feitelson and Salomon's (2004) framework is a useful starting point as it is a rare example of a framework that not only highlights a variety of factors influencing transport innovation but also conceptualises their interrelationships (see Figure 1). Systems thinking offers a methodological basis for investigating the interconnections between system elements and their outcomes (Sterman, 2002). It was first applied to transportation in the 1990s (Abbas & Bell, 1994) and it has since proven useful for studying the interdisciplinary nature of the transport sector. To a very limited extent, it has been applied to inland shipping. For example, Hou and Geerlings (2016) propose a system dynamics framework to evaluate the effectiveness of sustainable port and hinterland operations and Jiang et al. (2018) use it to analyse the economic impact of different governance modes.

One specific tool used in systems thinking literature is the Causal Loop Diagram (CLD), which can be used to capture the dynamic structure of systems (Hjorth & Bagheri, 2006). This dynamic structure is represented by factors connected with arrows that represent causal relationships between factors. These causal relationships can be positive (an increase in the value of one factor increases the value of another factor) or negative (an increase in the value of one factor decreases the value of another factor). A CLD not only captures causal relationships between pairs of factors, but also longer causal chains. These causal chains can constitute feedback loops, through which factors feed back onto themselves. Depending on the nature of the causal relationships that constitute these loops (i.e. positive vs. negative relationships), feedback loops can be reinforcing (amplifying effect) or balancing (dampening effect) (Meadows & Wright, 2008). Feedback loops are thus particularly useful in understanding how systems change or self-regulate. The effects of feedback loops can be counterintuitive, which is a key reason to expose them (Sterman, 1994). A common reinforcing loop in transport is the chicken-and-egg dilemma (Yao et al., 2024). An example of a balancing loop occurs when more resource availability enables scale-up, but more scale-up depletes resources (Bach et al., 2021). Feedback loops can differ in complexity. Some loops involve just two elements with a bidirectional causal relationship.

Table 1. Non-exhaustive overview of factors influencing transport and inland shipping innovations.

| Factor	Influence on	References
Eligibility of vessels and infrastructure	Fuel competitiveness; industry interest	Linzenich et al. (2023)
	Scale-up / adoption	Wee et al. (2022); CCNR (2022); Bach et al. (2021); Verberght (2020)
Business case	Industry interest; initial investments	Bach et al. (2021); Linzenich et al. (2023); CCNR (2022); Roso et al. (2020); Temenos et al. (2017); Verberght (2020); Hekkenberg & Liu (2017)
	Policies; Regulations	Bach et al. (2021); Temenos et al. (2017)
Industry interest	Initial investment; scale-up / adoption	Bach et al. (2021); Linzenich et al. (2023); Pel et al. (2022); Feitelson & Salomon (2004)
	Business case	Bach et al. (2021)
Benefits outweighing costs	Industry interest	Linzenich et al. (2023); Hekkenberg & Liu (2017)
	Scale-up / adoption	Feitelson & Salomon (2004)
Scale-up / adoption	Uncertainty	Linzenich et al. (2023)
	Resource availability	Bach et al. (2021)
Collaboration	R&D	Bach et al. (2021)
	Scale-up / adoption	Verberght (2020)
Environmental performance	Industry interest; initial investments	Linzenich et al. (2023)
	R&D	Bach et al. (2021)
	Scale-up /adoption	Pel et al. (2022)
Resource availability	Fuel price; regulations; uncertainty; interest in other alternatives; scale-up	Bach et al. (2021)
	Industry interest	Linzenich et al. (2023)
Technical differences and challenges (e.g. safety, effectiveness, technical readiness)	Eligibility of vessels and infrastructure; uncertainty	Bach et al. (2021)
	Industry interest; scale-up / adoption	Bach et al. (2021); Linzenich et al. (2023); CCNR (2022)
	Scale-up /adoption	Feitelson & Salomon (2004); Tsakalidis et al. (2020)
Uncertainty / unknown	Industry interest	Linzenich et al. (2023)
	Scale-up /adoption	Pel et al. (2022)
Readiness of other alternatives	Scale-up /adoption	Bach et al. (2021)
Economic instruments	Business case; fuel competitiveness	Linzenich et al. (2023); Tsakalidis et al. (2020); Verberght (2020); Hekkenberg & Liu (2017)
	Scale-up / adoption	Wee et al. (2022); Temenos et al. (2017); Verberght (2020); Hekkenberg & Liu (2017); Maraš (2017)
	R&D	Bach et al. (2021); Verberght (2020)
Information & communication	Industry interest	CCNR (2022)
	Scale-up / adoption	Wee et al. (2022); Verberght (2020)
Legal instruments	Uncertainty; initial investments	CCNR (2022)
	Scale-up / adoption	Temenos et al. (2017); Tsakalidis et al. (2020); Verberght (2020); Bach et al. (2021)
Policies	Scale-up / adoption	Wee et al. (2022); Pel et al. (2022)
	Uncertainty	Bach et al. (2021); Van Geenhuizen & Nijkamp (2003)
	R&D	Bach et al. (2021)
R&D	Technical differences & challenges	Tsakalidis et al. (2020); Van Geenhuizen & Nijkamp (2003); Hekkenberg & Liu (2017)
	Scale-up / adoption	CCNR (2022); Wee et al. (2022); Temenos et al. (2017); Feitelson & Salomon (2004); Verberght (2020); Hekkenberg & Liu (2017)
	Collaboration	Hekkenberg & Liu (2017)
Regulations	Uncertainty; initial investments	CCNR (2022)
	Scale-up / adoption	Wee et al. (2022); Verberght (2020); Hekkenberg & Liu (2017); Maraš (2017)
	R&D	Hekkenberg & Liu (2017)
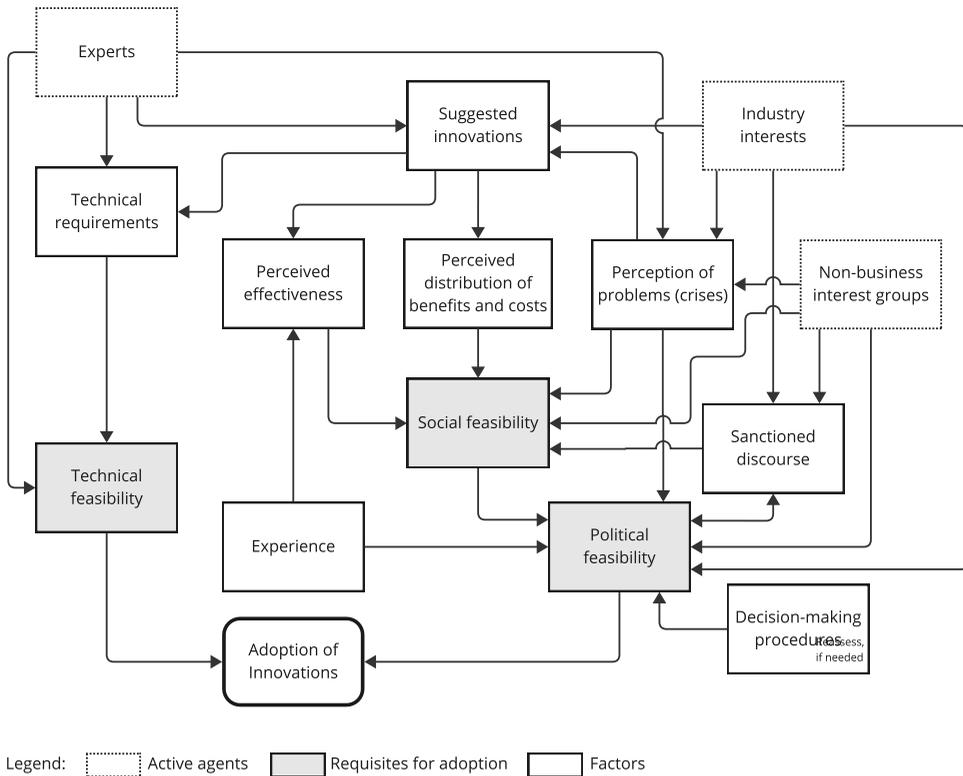
Figure 1. The political economy model of Feitelson & Salomon (2004).

However, feedback loops are also frequently formed by longer chains of causally related factors. Moreover, feedback loops can also interact with each other, constituting highly complex dynamic structures (Rhee, 2000).

This study uses the concept of mechanisms to depict specific segments of the dynamic structures captured in CLDs (Hedström, 2005). These mechanisms describe regular behaviour of parts of the dynamic structures in the CLDs. Mechanisms include chains of causal relationships between two or more factors. Usually, they also involve one or more feedback loops, as these are often responsible for producing regular behaviour. The different causal relationships involved in mechanisms are sometimes contradictory, where one causal pathway implies a positive influence between two factors, but an alternative pathway implies a negative influence. Identifying and interpreting mechanisms enables a qualitative description of a CLD, which is an important step in identifying bottlenecks for the scale-up of transport innovations. With further empirical research and quantitative modelling techniques, it is possible to identify leverage points that can improve the chances of success of alternative fuels in the inland shipping sector.

3. Methods for identifying mechanisms

This study explored dynamics influencing the scale-up of alternative fuels in the Dutch inland shipping sector by transforming textual data into CLDs. Qualitative

approaches for building CLDs have gained traction due to their ability to capture complex system relationships using actors' perspectives (see e.g. Lara et al., 2023; Tomoaia-Cotisel et al., 2022; Yearworth & White, 2013). To capture diverse knowledge, three types of textual data were collected and analysed: news articles, scientific articles and expert interviews. News articles typically depict non-technical situations, providing insights into industry debates, trends and strategies. Scientific articles typically contain technical and economic information about innovations. Expert interviews provide in-depth insights into industry challenges and the relationships between factors as experienced by the industry. Policy documents and industry reports were excluded from this study because they often present aspirational narratives rather than actual behaviour, making them less suitable for identifying causal relationships between factors. Key insights from these sources were expected to emerge through interviews with industry and policy experts, ensuring sector knowledge was still incorporated.

A six-step methodology was followed (Figure 2). The process started by selecting three fuels (Step 1) – an approach broad enough for data comparison but focused enough to study scale-up factors. Afterwards, news articles and scientific articles were collected (Step 2). Content analysis using qualitative coding was conducted to identify factors (Step 3) and relationships in the dataset (Step 4), which were mapped into CLDs (Step 5). Expert interviews were conducted (Step 6) to triangulate
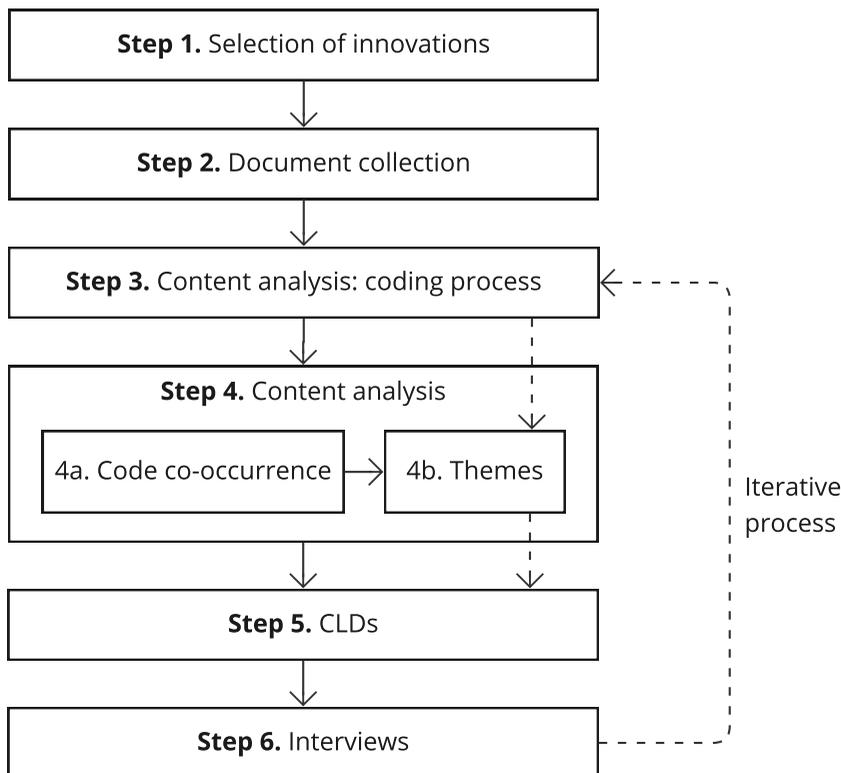

Figure 2. Six steps to transform textual data into CLDs.

the findings from data drawn from news and scientific articles. Interview data was ana-lysed as in Step 3, with the relationships from Step 4 further developed and the findings incorporated into the CLDs. This demonstrates the iterative process of integrating textual data into CLDs, rather than prioritising expert knowledge over news and scien-tific data.

3.1. Step 1. Selection of innovations

A search query in the news database LexisNexis was done using terms related to inland shipping, the Netherlands and innovations. Only news articles from the newspaper *Nieuwsblad Transport* were selected because it has the largest reach in the transport sector in the Netherlands, with 750,000 page views per month (Nieuwsblad Transport, 2025). It provides in-depth coverage of inland shipping developments, often including interviews with industry professionals. Additionally, its data are easily accessible via Lex-isNexis. This search query yielded more than 1,800 articles. For practical reasons, only the first 100 best matches were read. These were published between 2009 and 2022. Energy-related innovations were coded using Atlas.ti23 software to identify how many articles mentioned each innovation (Table 2). The decision to focus on hydrogen, LNG and biofuels was made for three reasons. First, these fuels can be used in various types of vessels, regardless of the goods they transport. In contrast, exchangeable battery containers – a popular innovation in the sector – are currently limited to con-tainer vessels. Their pioneer, Zero Emission Services, suggests they could eventually be powered by hydrogen (Zero Emission Services, 2021), highlighting hydrogen's potential role in driving other innovations. Second, they represent specific innovations, making them suitable for studying scale-up factors. Third, they have different levels of techno-logical readiness, allowing for the study of high-maturity innovations (e.g. LNG), which offer lessons from past experiences, and low-maturity innovations (e.g. hydrogen), which guide future interventions.

3.2. Step 2. Document collection

Search queries in LexisNexis, Scopus and WoS were done. The reliability of LexisNexis as a source of news articles for the study of the dynamics of innovations has been established in previous studies (Tziva et al., 2020). The only difference with the strategy in Step 1 was that the term 'innovation' was replaced by 'hydrogen', 'biofuels' or 'LNG'. This search

Table 2. Frequency of innovations in selected news articles.

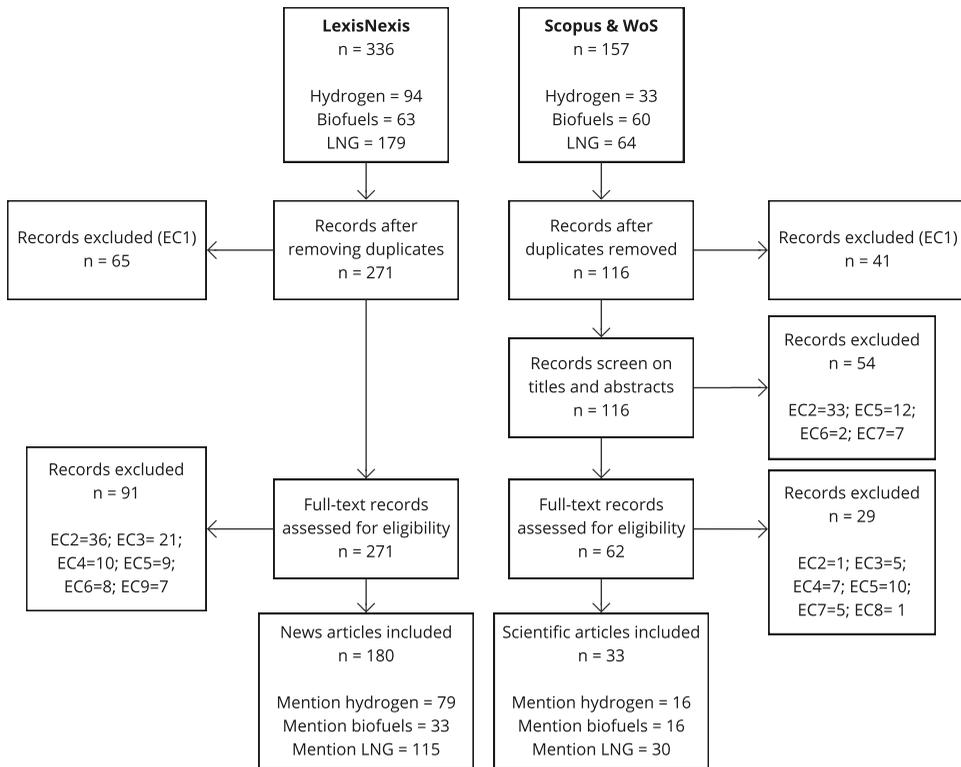| Innovation	N
Hydrogen	19
Electricity	17
Cleaner engines	15
LNG	12
Exchangeable battery containers	12
Stage V	10
Biofuels	7
Methanol	6
Ammonia	2

Figure 3. Data collection process for news and scientific articles on selected innovations.

Note: EC: exclusion criteria (1) duplicates, (2) different subject, (3) different transport mode, (4) focus on fuel transport, (5) different location, (6) no-content text, (7) text unavailable, (8) different timeframe, (9) different innovation.

yielded 336 news articles, with over half resulting from the LNG search, confirming its high maturity. The search in Scopus and WoS, which yielded 157 results, was done in English and was limited to articles, conference papers, reviews, and book chapters. After removing duplicates and irrelevant documents, 180 news articles (2009-2022) and 33 scientific articles (2009-2023) were analysed (Figure 3).

3.3. Step 3. Content analysis: coding process

The coding of scientific and news articles began with a codebook based on factors influencing transport and inland shipping innovations (see Table 1). However, this was an inductive process in which codes were modified or added based on the data. Ultimately, 32 codes were organised into 7 groups because they represented similar phenomena (Figure 4). For example, the codes *hydrogen*, *LNG*, and *biofuels* were grouped into the group *Innovations* because they all represent new fuels in the sector. The first code group (1) was used for selected innovations, while the other code groups (2–7) were used for scale-up factors. Coding rules were used for consistency in the process, e.g. the code *cooperation* was used only when specific collaboration actions such as 'sharing information' appeared in the text.
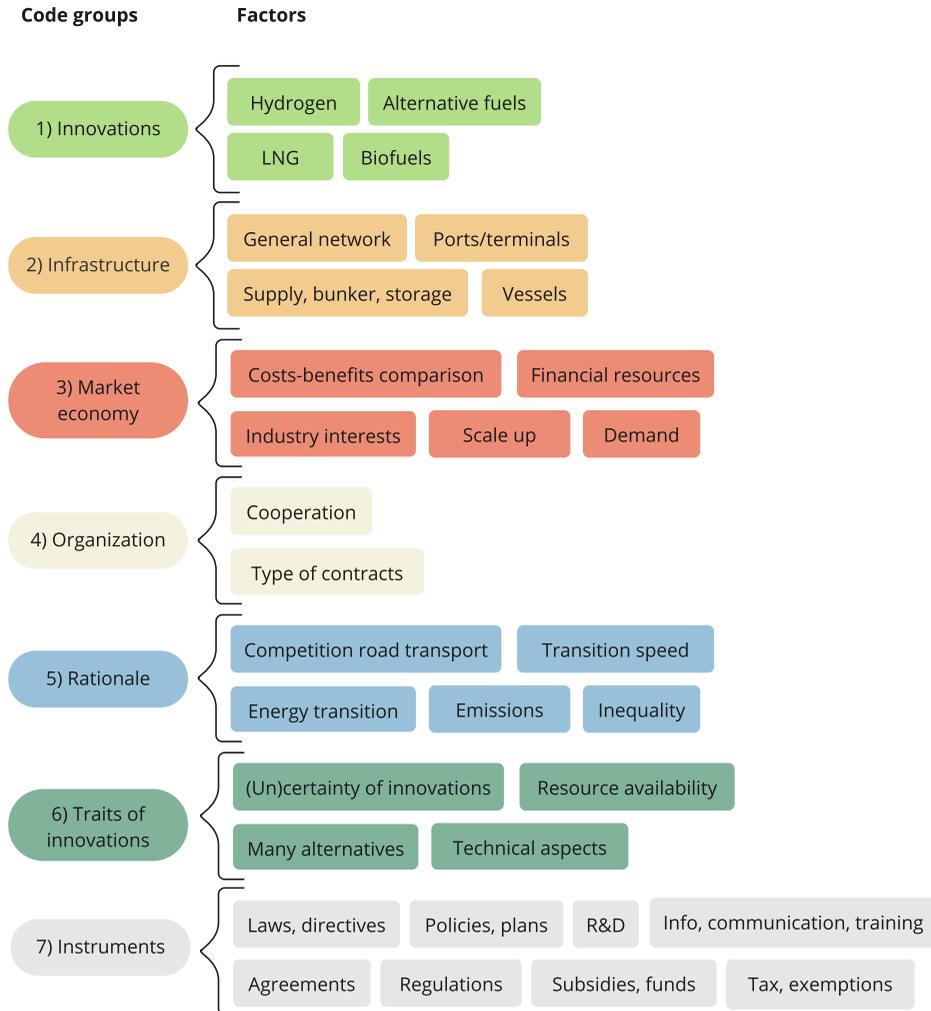
Figure 4. Code groups and codes.

3.4. Step 4. Content analysis: code co-occurrence and themes

A code co-occurrence analysis was done to reveal potential causal relationships between scale-up factors and innovations by identifying how often codes representing these appeared together in the text (Step 4a) (see a similar approach in Yearworth & White, 2013). Thus, codes for innovations (*hydrogen*, *biofuels*, and *LNG* in Group 1) were ana-lysed alongside codes for scale-up factors (codes in Groups 2–7). This resulted in a co-occurrence table, where a coefficient from 0 to 1 revealed how often an innovation was coded with scale-up factors (0 = the two codes do not co-occur, 1 = the two codes co-occur whenever they are used). A threshold of 0.05 was used to study factors that co-occur at least 5% of the time with the innovations. This resulted in 11 factors for bio-fuels, 13 for hydrogen and 20 for LNG. To determine causal relationships, the authors reviewed all quotations coded with an innovation and a scale-up factor. The information in the quotations was interpreted, and when multiple quotations led to a similar interpretation, a theme that summarises one or more relationships between codes was

Table 3. Data analysis process: from quotations to themes.

Quotation	Interpretation	Theme
'The biofuel blending obligation […] was initially going to be introduced this year for fuel suppliers to inland shipping, but this will now only be implemented in 2023 following a decision by the ministry. Several members have reported to us that the quality of biofuels still leaves much to be desired. For example, reports were received of filters that were clogged and engines that failed.'	• The ministry has postponed the biofuel blending obligation due to the potential risks of biofuels to engines. • Technical issues such as clogged filters and engine failures are reported.	Some industry actors believe that biofuels have technical risks. This was one of the reasons the Ministry did not introduce the mandatory blending obligation for biofuels. Code relationships included: • + Technical challenges → – Laws stimulating biofuel scale-up in NL • + Technical challenges → – Industry interest
'The NEN, the Dutch Standardization Institute, is currently conducting a study into the effects of blending biodiesel. Only when the results of the NEN report are known will Minister Visser reconsider whether admixture should be mandatory. Industry association ASV wrote in an earlier letter to the minister that 'FAME is a silent killer'.'	• The ministry will consider the biofuel blending obligation once reports on the effects of the biofuel mix are completed. • The industry believes that FAME damages engines.	
'Biofuels received numerous reports from skippers who experienced problems due to mixed biodiesel. In discussions with the ministry, ASV and ship insurer EOC have repeatedly emphasized these risks'	• The industry believes that the biofuel mix damages engines. • The industry has shared this with the ministry.	

created (Step 4b). From the themes, it was possible to hypothesise whether the influence between factors was positive or negative (see example in Table 3) (see a similar approach in Tomoaia-Cotisel et al., 2022).

3.5. Step 5. CLDs

The themes and the relationships described in them were used to develop three CLDs, each showcasing the relationships between factors influencing the scale-up of hydrogen, biofuels and LNG. Appendix A provides examples of news articles, scientific articles and interviews (see Step 6) that discuss and support the relationships represented in the three CLDs. The different ways in which the factors are connected reveal multiple causal links and feedback loops, which are represented in the CLDs. Ultimately, tracing and interpreting these causal links and feedback loops enabled the identification of mechanisms. Mechanisms are composed of groups of factors that are interrelated, and through their interrelations they regularly produce the same outcome (Hedström, 2005). Mechanisms show the underlying cause-and-effect relationships between factors that influence the scale-up of these alternative fuels and thus can be used to explain the overall behaviour of the dynamic structures depicted in the CLDs.

3.6. Step 6. Interviews

Twelve interviews with experts in the field (see Appendix B) were conducted for triangulation purposes. As employees in the sector, their knowledge is highly relevant for

identifying factors that may influence their decisions regarding the use of alternative fuels. During the interviews, participants were presented with the CLDs and asked specific questions about the factors and relationships depicted (see Appendix C). They were invited to reflect on these dynamics and share concrete examples from their experiences. Interviews were recorded and transcribed using the Amberscript software. The text was analyzed as in Step 3, and the themes from Step 4b were further developed, creating an iterative process between textual data and the CLDs. The interviews were used to cross-check the findings emerging from the CLDs (i.e. factors and causal relationships), as well as identify gaps and improve clarity. It is important to note that the interview data did not result in new factors, but did draw attention to factors and relationships that had been previously excluded for not meeting the 5% co-occurrence threshold set in Step 4a.

4. Findings

In the construction of the CLDs, the following three simplifying decisions were made to reduce complexity, ensure feasibility, and answer the research question. First, to address the slow transition of the Dutch inland shipping sector, the scope is limited to this sector, excluding interactions with other transport modes. Second, industry actors are grouped due to the low granularity of data, which makes it difficult to distinguish how different industry actors influence different factors and their relationships. Third, since infrastructure is inherently linked to the development of vehicles (Calderón-Rivera et al., 2024), vessels, and infrastructure form one factor, making no distinction between different types of facilities. Figures 5–7 show the CLDs for each of the studied fuels. A first observation is that the three CLDs have many similarities. For this reason, one is explained in detail, while the differences between the other two are presented in brief. A second observation is that the CLDs include multiple feedback loops, as well as causal pathways between factors showcasing counterintuitive changes, trade-offs, and contradictory effects. These feedback loops and dynamics are embedded in mechanisms describing the self-regulating nature of the system (for detailed information see Appendix D), which are the main foci of the analysis. This study has also found multiple instruments, deployed by both public and private actors, that attempt to influence the system.

4.1. Biofuels

The CLD of biofuels is shown in Figure 5. It is important to note that most documents and interviewees referred to drop-in biofuels, that is HVO (Hydrotreated Vegetable Oils) and FAME (Fatty Acid Methyl Esters). From the composition of factors and dynamics influencing the scale-up of biofuels, six main mechanisms have been identified.

Mechanism 1. The reinforcing role of cost–benefit assessment

The first mechanism revolves around the observation that the industry's interest in adopting biofuels is driven by an assessment of whether the benefits outweigh the costs. Environmental and economic factors play a role in this assessment. The environmental benefits of biofuels are contested: biofuels produce fewer emissions during combustion compared to diesel, but their true emissions depend on their source materials
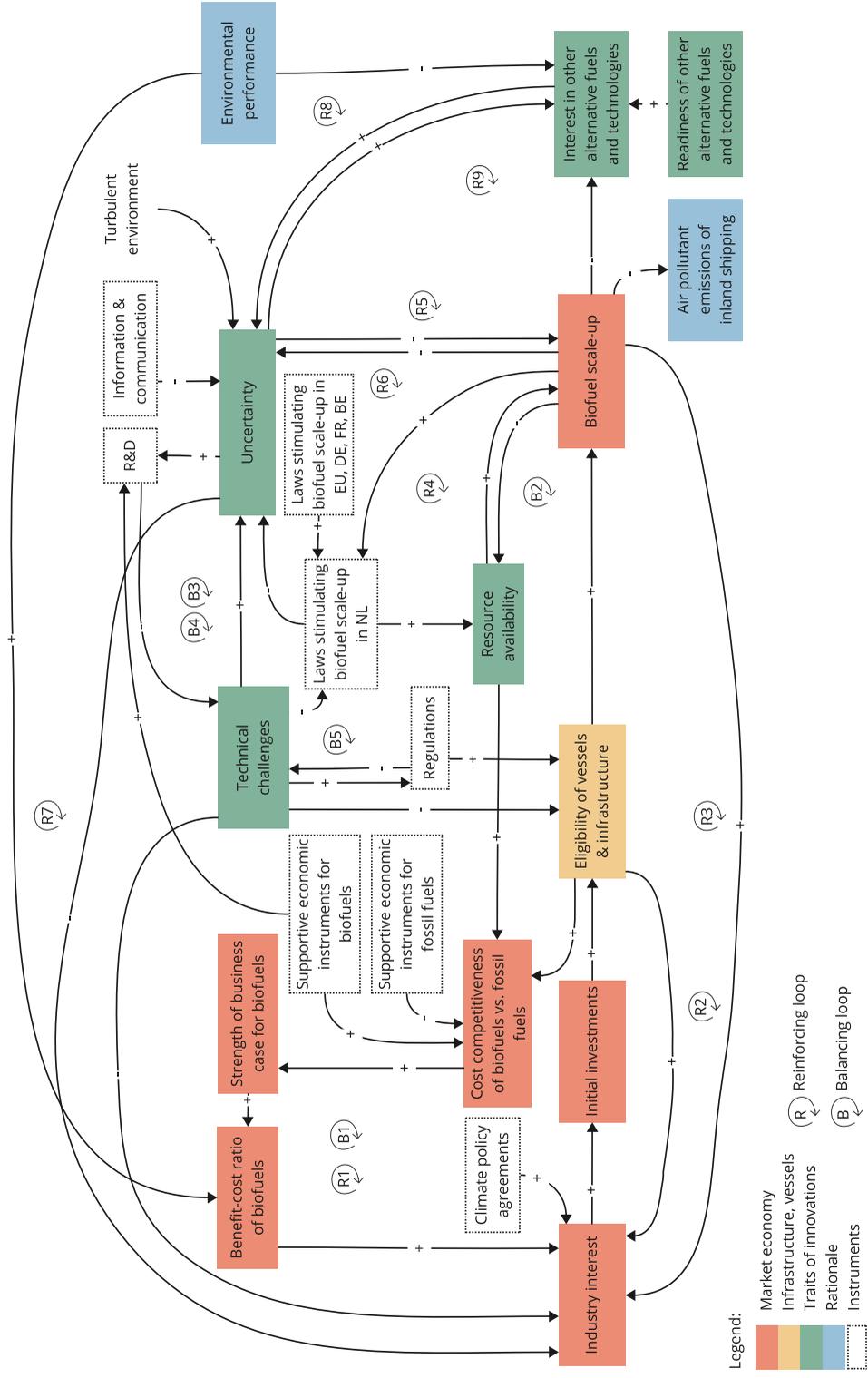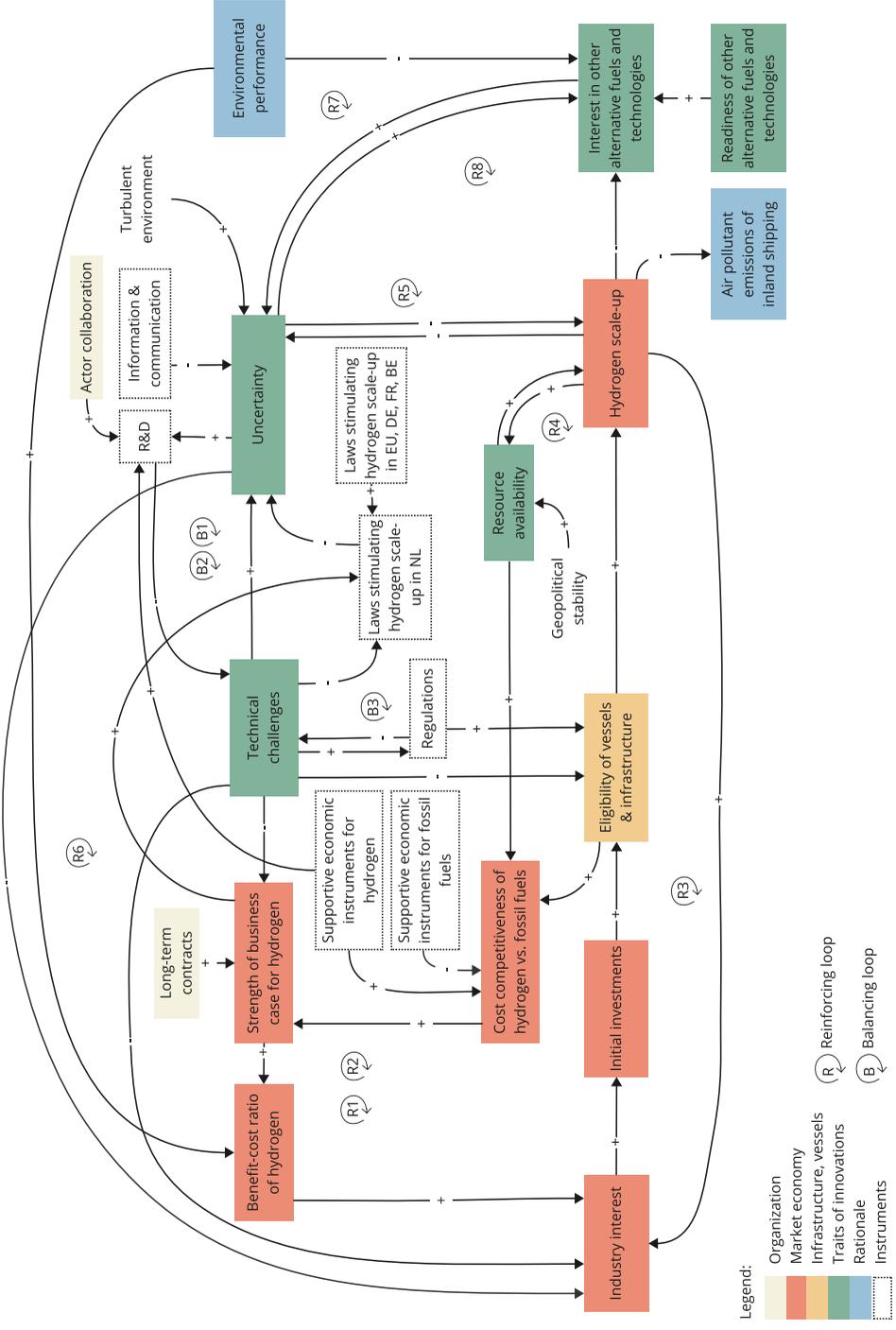
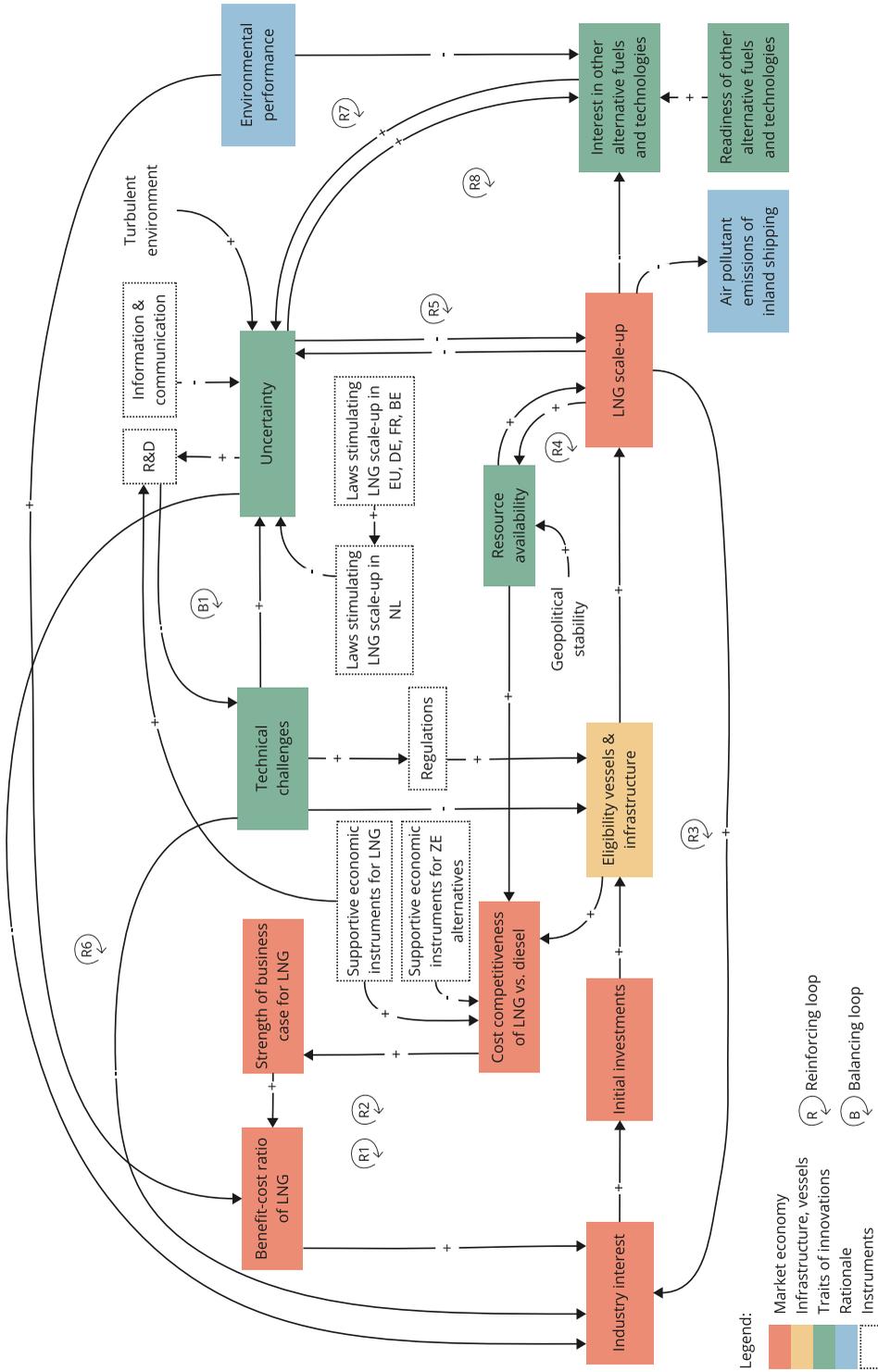**Figure 5.** Biofuels CLD.

Figure 6. Hydrogen CLD.

Figure 7. LNG CLD.

and production methods. The main economic factor influencing this assessment is the status of the business case (i.e. whether a fuel is financially viable and beneficial). This is dictated by the competitiveness of biofuels relative to fossil fuels, which includes the biofuel-fossil fuel cost ratio, and the perceived investments needed to ensure eligibility of vessels and infrastructure. However, an important nuance that most interviewees introduced is that drop-in biofuels require no or relatively small investments, especially HVO. If the industry's assessment is that the benefits outweigh the costs, this can set in motion a reinforcing feedback loop that leads to growing industry interest and investments and subsequently to increased eligibility of vessels and infrastructure. This then creates economies of scale that improve the competitiveness of biofuels, ultimately strengthening the biofuel business case. However, the inverse is also true: If the industry assesses that the benefits do not outweigh the costs, this sets in motion a reinforcing feedback loop in the other direction, where industry interest decreases, leading to fewer investments in improving the eligibility of vessels and infrastructure. This prevents economies of scale and decreases the competitiveness of biofuels, which reinforces the industry assessment that the benefits do not outweigh the costs, decreasing interest even further (Loop R1).

Mechanism 2. The balancing role of limited resource availability

The second mechanism describes how the limited availability of biofuel resources plays a balancing role in regulating their competitiveness, subsequently influencing industry interest. As described in the first mechanism, higher industry interest leads to more investments and increases the eligibility of vessels and infrastructure, which increases scale-up. However, since biofuels are limited, scaling up puts pressure on the available resources. Limited resource availability increases the price of biofuels, which decreases competitiveness and industry interest (Loop B1). Therefore, while increased industry interest generates economies of scale and increases biofuel competitiveness, it also depletes resources and increases the price of biofuels, which decreases biofuel competitiveness. Mechanism 2 thus balances the reinforcing feedback loop identified as part of mechanism 1.

Mechanism 3. Technical challenges decrease industry interest and scale-up

This mechanism describes how technical differences (between biofuels and fossil fuels) and the challenges this can cause negatively impact industry interest and scale-up. Higher technical differences and challenges decrease the eligibility of vessels and infrastructure due to required modifications, which in turn decreases industry interest. However, as described in mechanism 1, this may be unnecessary or minimal with drop-in biofuels, depending on vessel characteristics such as age, engine type, or engine certification. Lower industry interest leads to lower investments, and, therefore, lower eligibility of vessels and infrastructure (Loop R2). This decreases scale-up, further decreasing industry interest, investments, and eligibility of vessels and infrastructure (Loop R3).

Mechanism 4. Limited resource availability influences uncertainty

The fourth mechanism revolves around the idea that biofuels are limited, which increases uncertainty and decreases scale-up. Legal instruments stimulating the production and consumption of biofuels (e.g. EU directives) increases biofuel scale-up, which further drives interest in legal instruments (Loop R4). However, since biofuels are limited, this creates a challenge: as scale-up occurs, resources are depleted, preventing further scale-up (Loop B2). This challenge discourages the usage of legal instruments, which generates uncertainty about the future of biofuels. An increase in uncertainty has three reinforcing effects: it decreases scale-up (Loop R5), discourages the usage of legal instruments (Loop R6), and decreases industry interest (Loop R7), all of which further increase uncertainty.

Mechanism 5. Technical challenges drive uncertainty

The fifth mechanism describes how technical challenges in using biofuels decrease industry interest and increase uncertainty, as they raise questions about safety. Higher uncertainty emerging from technical challenges stimulates R&D to address these challenges and lower uncertainty (Loop B3). However, when these technical challenges discourage the usage of legal instruments stimulating the production and consumption of biofuels, such as a blending obligation, it increases uncertainty about the future of biofuels. While R&D can help address uncertainty (Loop B4) it does not resolve all forms of uncertainty: R&D typically addresses uncertainty related to technical challenges, rather than broader uncertainty about the future role of biofuels in the energy transition.

Mechanism 6. Fuel alternatives influence uncertainty

This sixth mechanism highlights how the characteristics of biofuels contribute to uncertainty. The challenges in scaling-up biofuels due to their limited availability, and their contested environmental benefits, increase interest in other alternative fuels and technologies. A paradox occurs where biofuels' environmental performance has positive and negative implications for their scale-up; while their sustainability – compared to fossil fuels – drives industry interest, their non-ZE status makes them a temporary solution until ZE alternatives are ready. Interest in other alternatives and doubts about what fuels will constitute the future energy mix increase uncertainty about biofuels, which further increases interest in other alternatives (Loop R8). Higher uncertainty decreases scale-up, which again leads to interest in other alternatives and increased uncertainty (Loop R9).

Instruments

Six types of public and private instruments influence biofuels' scale-up. An increase in *instrument* factors should be understood as reflecting either a greater number of certain instruments (e.g. more laws) and/or more effective instruments (e.g. more appropriate regulations). Economic instruments are diverse and can have positive or negative implications for the competitiveness of biofuels. For example, the existing tax exemption of fossil fuels decreases biofuel competitiveness, whereas the upcoming EU Emission Trading System will increase it. Several instruments are used to address uncertainty, including information and communication campaigns, subsidised-R&D and legal

instruments. To ensure a level playing field, it is important that these legal instruments are implemented by the EU or in accordance with neighbouring countries. Regulations play an important role in addressing technical challenges, for example, by stipulating the components of the biofuel mix and reducing the risks of engine damage. At the same time, higher technical challenges require regulations such as engine certification (Loop B5). Lastly, the need to abide by agreements, such as the Paris Agreement or the Green Deal, increases industry interest in adopting biofuels.

Empirical observations

Above, the mechanisms are presented in their abstract form, but based on the sources from which they were derived it is also possible to say something about how they play out in practice. One important empirical observation is that several industry actors do not believe that the benefits of biofuels outweigh their costs (mechanism 1). While the overall environmental benefits of biofuels are contested at a national scale, their use in the inland shipping sector could nonetheless contribute to reducing air pollution (mainly CO_2 and PM) from vessels. Moreover, a strong business case is lacking, due to higher fuel costs, which are expected to increase further from competition with the aviation sector, and higher initial investments – though these are relatively low for drop-in biofuels such as HVO (mechanism 2). While this makes biofuels the preferred alternative by many, technical challenges have emerged with FAME, leading industry actors to question biofuels' safety. Interviewees reported that having engine certification and subsequent insurance coverage would likely address these concerns and increase interest (mechanism 3). These technical challenges, together with concerns about the limited availability of biofuels, were among the reasons the blending mandate was never implemented. It was speculated that this mandate would decrease uncertainty by giving direction and assurance to industry actors, ultimately increasing scale-up (mechanisms 4 and 5).

4.2. Hydrogen

The CLD of hydrogen is shown in Figure 6. The same six mechanisms described above are useful to describe the dynamics influencing hydrogen scale-up. However, the perception of hydrogen as a potentially abundant resource changes mechanisms 2 and 4. Hydrogen (H_2) is the most abundant element on Earth, but it is primarily found in water (H_2O). Significant energy is required to separate hydrogen before it can be used as a fuel. However, if the necessary procedures and technologies become available, hydrogen could become an abundant energy source for vessels. In this context, higher industry interest and subsequent scale-up increases resource availability (as suppliers increase production) which in turn increases scale-up (Loop R4). Higher resource availability reduces the price of hydrogen, increasing its competitiveness and thereby industry interest (Loop R2). Essentially this means that with time, the costs of adopting hydrogen will tend to decrease. Thus, rather than playing a balancing role, resource availability here further contributes to a reinforcing feedback loop that can improve the balance between costs and benefits of hydrogen.

Interviewees stated that long-term contracts between cargo owners and vessel operators can facilitate hydrogen scale-up, as this gives vessel operators the assurance that their investments and operational costs will be (partly) compensated. Like with biofuels, legal instruments can be used to decrease uncertainty and increase scale-up. However, an essential component here is the need for a strong business case that justifies the use of legal instruments stimulating production and consumption of hydrogen. Without a strong business case, legal instruments are not used to support resource availability, resulting in the absence of two reinforcing loops seen with biofuels.

Empirical observations:

It is evident that the benefits of using hydrogen do not currently outweigh the costs (mechanism 1). Although the environmental benefits are certain, this is only the case for green hydrogen (made of renewable energy and fuel cells) and to some extent blue hydrogen (when carbon is captured). Interviewees reported that substituting diesel with grey hydrogen (created from natural gas or methane) would be counterproductive. There is no business case for hydrogen due to extremely high prices and required investments, as hydrogen differs significantly from fossil fuels. The lack of infrastructure makes some vessels ineligible, such as those without fixed routes that would require a broad hydrogen network (mechanism 3). While currently the availability of hydrogen is limited due to limited infrastructure, interviewees consider hydrogen to be a potentially abundant resource, which makes it a promising alternative (mechanism 2 and 4). However, hydrogen is still in the early stages of development, and the sector is interested in more readily available alternatives (mechanism 6).

4.3. LNG

The CLD of LNG is presented in Figure 7. The six mechanisms that describe the dynamics of biofuels and hydrogen remain useful for understanding LNG scale-up. Given that LNG is seen as a widely available resource, the six mechanisms operate in the same way as they do for hydrogen. This means that, in comparison to biofuels, mechanisms 2 and 4 differ. Since LNG is a widely available resource, increased industry interest and subsequent scale-up increases resource availability, which in turn facilitates scale-up (Loop R4). Higher resource availability reduces LNG's price, increasing its competitiveness and thereby industry interest (Loop R2). As with hydrogen, one would expect the price of LNG to decrease with time. However, the LNG case shows that worldwide events creating a turbulent environment and geopolitical instability have important effects on resource availability, and therefore, on the competitiveness of LNG. This shows that an increase in scale-up alone does not guarantee an increase in the competitiveness of LNG.

Empirical observations:

Interest in LNG started in the early 2000s, driven by environmental benefits (reduced NOx and PM) and the favourable cost of LNG relative to diesel (mechanism 1). Unexpectedly, the Hiroshima disaster and later the Russia-Ukraine war created a turbulent

environment that increased LNG prices, turning a positive business case into a negative. This, together with increasing awareness of the importance of reducing GHG emissions, has decreased interest in LNG (mechanism 2). Behind the peak demand for LNG was a strong EU lobby, supported by subsidies, directives, R&D and regulations. Through multiple factors, these policy instruments positively influence LNG scale-up, decreasing uncertainty about its future. However, there appears to be a shift in ambitions from both the EU and the Dutch government, with the current policy instruments no longer directly supporting LNG scale-up. This shift might be driven by the fact that LNG is considered misaligned with zero-emission goals, which contributes to growing uncertainty and increasing interest in other fuels and technologies (mechanism 6). Given the long lifespan of vessels (50 years) and the fact that most vessel owners can only invest once in a sustainable alternative, the industry must adopt a long-term perspective. This means that, for many experts, LNG is not even a temporary solution.

4.4. Concluding remarks

To sum up, all six mechanisms can be used to describe the dynamics influencing the scale-up of biofuels, hydrogen and LNG. Mechanisms 1 and 2 are dominated by market/economic factors and are centred on the idea that the industry's interest depends on their assessment of benefits outweighing costs. Mechanism 3 emphasises the importance of technical factors and demonstrates their impact on scaling-up. Mechanisms 4, 5 and 6 highlight the central role of uncertainty, which is influenced by technical differences and challenges, scale-up and interest in other alternative fuels and technologies. Regarding the similarities between the three fuels, mechanisms 1, 3, 5 and 6 show the same feedback loops and dynamics. However, the fact that biofuels are seen as a limited resource whereas hydrogen and LNG are seen as abundant creates differences in mechanisms 2 and 4. These differences are of key importance. For example, the balancing role that resources play in the biofuel case (mechanism 2) reduces the opportunities for economies of scale, which exist in the other cases. The fact that opportunities for economies of scale (and as part of this, increased scale-up) are better for hydrogen and LNG does not necessarily mean that they occur. For example, empirical observations from the hydrogen case show that the benefits do not yet outweigh the costs due to the high investments required to develop suitable infrastructure. It is thus important to not just study the mechanisms in their abstract form but to study how they unfold in practice, using in-depth empirical data.

5. Discussion

This study examined the mechanisms explaining the scale-up (or lack thereof) of alternative fuels in the Duch inland shipping sector. This was done by constructing CLDs for three cases (biofuels, hydrogen and LNG) using literature and news articles from 2009 to 2023, as well as expert interviews conducted in 2024. The CLDs provide a dynamic, systemic representation of factors influencing fuel scale-up during this period, from which six common mechanisms have been identified. By interpreting these mechanisms across all three fuels, considering their interactions and empirical evidence, two key insights are distilled. These insights build on existing literature on transport innovations

and systems thinking. After presenting these insights, the limitations of the study and future research directions are explained.

5.1. Common mechanisms explain the dynamics of biofuels, hydrogen and LNG scale-up, with resource availability creating key differences

Six common mechanisms explain the dynamics of fuel scale-up in the sector. These include several interconnected factors, creating chains of events that are continuously changing (Pel et al., 2022; Temenos et al., 2017). Four of the six mechanisms are applicable across all three cases. Despite their similarities, the way they manifest in practice and their outcomes differ due to differences in the values that their constituent factors take on. This demonstrates the indeterminate nature of mechanisms, making them useful for explaining empirically observed outcomes, but not for predicting outcomes (Meadows & Wright, 2008).

Two of the six mechanisms operate differently for biofuels compared to hydrogen and LNG due to differences in the role that resource availability plays in them. Higher industry interest increases the competitiveness of all three fuels. However, for biofuels, the limited resource availability balances this effect (Biofuels: B1, B2). While resource availability has been previously identified as a factor influencing fuel price, scalability and industry interest (Bach et al., 2021; Linzenich et al., 2023), this study shows its ramifications for a broader set of innovation dynamics (Biofuels: B1, B2, R4; Hydrogen: R2, R4; LNG: R2, R4). The same can be said for other factors presented in Table 1. For example, this study supports the finding that uncertainty (i.e. the lack of information and not knowing what to do) influences transport innovation scale-up (Linzenich et al., 2023; Pel et al., 2022). Yet, the CLDs add depth to this insight, showing how uncertainty ultimately affects the dynamics of innovation in their entirety (Biofuels: B3, B4, R5-9; Hydrogen: B1, B2, R5-8; LNG: B1, R5-8). Thus, a systems thinking approach is necessary to understand the broader consequences of one factor in the system. This is in line with systems thinking, which emphasises the systemic structures that interconnected factors form, rather than the isolated influence of individual factors (Hjorth & Bagheri, 2006).

5.2. Adopting innovations requires a holistic approach

The three CLDs show that feedback loops are common (also see Hjorth & Bagheri, 2006). Reinforcing loops outnumber balancing loops (Biofuels: 4B < 9R; Hydrogen: 3B < 8R; LNG: 1B < 8R) and can work for or against the scale-up of alternative fuels, as they tend to enhance whatever direction of change is imposed on them (Meadows & Wright, 2008). While they currently reinforce the use of fossil fuels, they could also drive the use of alternative fuels, with the apparent exception of biofuels, which face resource limitations (Biofuels: B1, B2). The information provided by these feedback loops broadens the understanding of transport innovation dynamics and shows that incremental and well-controlled optimisation approaches are too simplistic (Pel et al., 2022). This study has found several system dynamics, including counterintuitive changes, trade-offs and contradictory relationships (Sterman, 2002). While these dynamics can be broken down into several mechanisms, ultimately, they interact (e.g. B2 in Biofuels belongs to mechanism 4, but is also part of B1 in mechanism 2).

Consequently, attempts to influence these dynamics should not focus on just one mechanism. Indeed, this study indicates that achieving systemic change requires a holistic approach (Hjorth & Bagheri, 2006). This is essential to identify bottlenecks, which hinder innovations' scale-up, and leverage points, where instruments can be used to produce system changes. This study has identified several public and private instruments, which can be used to influence different factors (e.g. Biofuels R4, Hydrogen B2, LNG B1). Although the identified mechanisms at this point cannot yet be used to predict the exact impact of these (and other) instruments, it is possible to identify priority factors. The most common factors in feedback loops and mechanisms are *uncertainty* (appearing in 7/13 Biofuels loops, 6/11 Hydrogen loops, and 5/9 LNG loops) and *industry interest* (appearing in 5/13 Biofuels loops, 4/11 Hydrogen loops, and 4/9 LNG loops), suggesting that these could have the broadest system-impact. However, their deep embeddedness in the system also suggests that attempts to influence these factors can have extremely counterintuitive and contradictory results (Sterman, 2002), highlighting once more the importance of a holistic approach. Thus, more empirical research is needed to explore what instruments are appropriate to address leverage points for future interventions and especially how instruments can be used in concert to enable a holistic approach.

As discussed in Section 2, many studies have reported factors influencing the scale-up of transport and inland shipping innovations (Verberght, 2020; Wiegmans & Konings, 2017). However, few studies have investigated the dynamic interrelations of factors and the complex causal structures that these form (Hou & Geerlings, 2016; Pel et al., 2022). Hence, a key contribution of this study is to provide a more comprehensive overview – in the form of CLDs – of the dynamics of transport innovation, with a focus on alternative fuels. The existence of mechanisms that reinforce fossil fuel use resonates with global inland shipping trends, where the energy transition is also slow and is challenged by faster innovation in other transport modes. However, further research is needed to determine if these mechanisms hold in other countries with different institutional, political and organisational contexts.

5.3. Limitations and future research

The findings of this paper need to be considered within a set of limitations. First, the case selection excluded other key innovations, particularly batteries, which are increasingly relevant in the sector. Thus, the study may not fully capture the diversity of scale-up mechanisms for reducing emissions. Further empirical research is needed to determine whether the findings apply to other innovations. Second, the analysis included more news articles than academic articles – largely excluded for focusing on technical aspects rather than scale-up factors and their relationships. This may have resulted in an incomplete account of the innovations' technical barriers. News articles were necessary to capture the underrepresented societal, organizational and political factors in the literature. However, they may be biased by editorial agendas, personal opinions and public appeal, potentially influencing the findings by overreporting technical challenges or presenting an overoptimistic view of certain innovations. To address this, the study triangulated the data with academic articles and expert interviews. Future research can include other data sources such as industry reports. Last, the CLDs include some factors that are multidimensional, such as *industry interests*, *uncertainty* and *regulations*.

These factors take on a simplified form as the resolution of the data is too low to reliably distinguish the causal influence of their different types. This means that the multiple (conflicting) interests of different actors and the regulatory complexity of the sector are not considered, limiting the possibility of understanding how different actors and institutions influence the dynamics of innovations. Future research is necessary to zoom in on the different dimensions of these factors and develop a more fine-grained understanding of their causal relationships with other factors.

One important line for further work is using the conceptual model of this study to build quantitative simulation models and conduct scenario analysis. The in-depth results of the CLDs can help conceptualise the system's hypothesised behaviour (its key factors and relationships), necessary for the formulation of quantitative models (Lara et al., 2023). Quantitative models would enable the incorporation of stocks-and-flows, capturing the impact of time in the system and showcasing the current scale-up status of the fuels. Scenario analysis could then be used to explore different actions for system change, possibly serving as the basis for more concrete policy recommendations.

6. Conclusion

The energy transition of the Dutch inland shipping sector has been progressing slowly. This study set out to explore why the sector has not widely scaled-up alternative fuels. Using scientific papers, news articles, and expert interviews to build CLDs, this research explores the mechanisms influencing the scale-up – or lack thereof – of alternative fuels in the sector. Six mechanisms, made up of interconnected factors and feedback loops, describe the scale-up dynamics of biofuels, hydrogen and LNG. Four mechanisms (#1, 3, 5, 6) are common across all three fuels, while two mechanisms (#2, 4) differ due to differences in the perceived availability of the fuels' resources. First, a positive cost–benefit assessment drives industry interest and fuel competitiveness, while a negative assessment reduces investment and reinforces high costs. Second, perceived resource availability influences scale-up: limited biofuel resources decrease competitiveness and scale-up, while abundant resources for hydrogen and LNG increase competitiveness and scale-up. Third, technical challenges emerging from technical differences between these fuel alternatives and fossil fuels decrease vessel and infrastructure eligibility, decreasing industry interest and reinforcing the slow scale-up. Fourth, limited biofuel resources increase uncertainty and reduce legal support, reinforcing uncertainty. While legal support could reduce uncertainty for hydrogen and LNG, a negative business case hampers this. Fifth, technical challenges increase uncertainty, which R&D can address. However, R&D does not reduce uncertainty about the future of different alternatives in the energy transition. Sixth, the challenges and slow scale-up of each alternative increase interest in other options, creating uncertainty about their future and reinforcing the slow scale-up.

These mechanisms have explanatory value: they can explain patterns in the behaviour of the system when used with empirical data. However, they cannot predict the future behaviour of the system. Although this limits the possibility to give specific recommendations to policymakers and industry actors, it highlights key factors for future research and interventions. *Industry interest* and *uncertainty* are the most common factors in the feedback loops and mechanisms, suggesting their broad system-impact. Industry interest

is influenced by cost–benefit assessment, resource availability and technical challenges. The role of uncertainty is evident in its presence across multiple feedback loops, where it is influenced by resource availability, technical challenges and fuel alternatives. Prioritising these factors does not imply they should be treated independently. Their deep embeddedness in the system means that addressing them can lead to counterintuitive and contradictory effects (Sterman, 2002). This resonates with the systems thinking idea that 'you can't just do one thing' (Sterman, 1994, p. 291), which hinders the possibility to create concrete policy recommendations. Nevertheless, this study can raise policymakers' awareness of systemic complexity and support more informed decisions that consider counterintuitive and contradictory effects. The use of quantitative and holistic approaches, such as modelling and scenario analysis, can be used to test the exact impact of specific interventions on the scale-up of these fuel alternatives and contribute to achieving a ZE inland shipping sector by 2050 (as suggested by Kirichek et al., 2023). A key contribution of this paper is providing an understanding of the system's conceptual mechanisms and hypotheses about its functioning, which are required for these quantitative approaches (Lara et al., 2023).

Disclosure statement

Funding

Ethics statement

Ethical approval was obtained from the ethics committee at Erasmus University Rotterdam (application ETH2324-0439). Permission to conduct the interviews for the purposes of this research was obtained by all respondents, who were fully informed about the purposes of this research and how their responses would be used and stored.

Data availability statement

Portions of the dataset generated and analyzed during this study are available in the Erasmus University Rotterdam repository, accessible via the following DOI: 10.25397/eur.27888366.

ORCID

Núria Coma-Cros 🔟 http://orcid.org/0009-0005-7458-9908
Wouter Spekkink 🔟 http://orcid.org/0000-0002-2773-4878
Ron van Duin 🔟 http://orcid.org/0000-0001-8099-5615
Jurian Edelenbos 🔟 http://orcid.org/0000-0002-8070-4547

References

Abbas, K. A., and M. G. H. Bell. 1994. "System Dynamics Applicability to Transportation Modeling." *Transportation Research Part A: Policy and Practice* 28 (5): 373–390. https://doi.org/10.1016/0965-8564(94)90022-1

Bach, H., T. Mäkitie, T. Hansen, and M. Steen. 2021. "Blending New and Old in Sustainability Transitions: Technological Alignment between Fossil Fuels and Biofuels in Norwegian Coastal Shipping." *Energy Research and Social Science* 74:e101957. https://doi.org/10.1016/j.erss.2021.101957.

Bakker, S., S. Moorman, M. Knoope, S. van Zyl, J. Moncada Botero, and H. Mulder. 2022. *Energy Chains for Carbon Neutral Mobility: Efficiency, Costsand Land use in Perspective.* https://english.kimnet.nl/publications/publications/2022/09/09/energy-chains-for-carbon-neutral-mobility.

C-230 Green Deal on Maritime and Inland Shipping and Ports. 2019.

Calderón-Rivera, N., I. Bartusevičienė, and F. Ballini. 2024. "Sustainable Development of Inland Waterways Transport: A Review." *Journal of Shipping and Trade* 9 (1): 3. https://doi.org/10.1186/s41072-023-00162-9.

Central Commission for the Navigation of the Rhine. 2022. *CCNR ROADMAP for Reducing Inland Navigation Emissions.*

European Commission. 2020. *Navigation and Inland Waterway Action and Development in Europe (NAIADES) III Action Plan 2021-2027.* https://www.consilium.europa.eu/en/press/press-releases/2020/06/05/towards-a-carbon-neutral-and-competitive-eu-.

European Commission. 2021. *Mobility and Transport.* Inland Waterways. https://transport.ec.europa.eu/transport-modes/inland-waterways_en.

European Commission. 2023, July. *Green Deal: Greening Freight for More Economic Gain with Less Environmental Impact.* European Commission Mobility and Transport. https://transport.ec.europa.eu/news-events/news/green-deal-greening-freight-more-economic-gain-less-environmental-impact-2023-07-11_en.

Eurostat. 2024. *Inland Waterway Transport by Nationality of Vessel and Coverage [Data set].* https://doi.org/10.2908/IWW_GO_ANAVE

Fan, A., J. Wang, Y. He, M. Perčić, N. Vladimir, and L. Yang. 2021. "Decarbonising Inland Ship Power System: Alternative Solution and Assessment Method." *Energy* 226:e120266. https://doi.org/10.1016/J.ENERGY.2021.120266.

Feitelson, E., and I. Salomon. 2004. "The Political Economy of Transport Innovations." In *Transport Developments and Innovations in an Evolving World*, edited by M. Beuthe, V. Himanen, A. Reggiani, and L. Zamparini, 11–26. Berlin & New York: Springer-Verlag.

Filarski, R., and G. Mom. 2008. *Van transport naar mobiliteit: De transportrevolutie 1800- 1900 [From Transport to Mobility: The Transport Revolution 1800- 1900]* (Stichting Historie der Techniek, Ed.). Walburg Pers.

Forrester, J. W. 1994. "System Dynamics, Systems Thinking, and Soft OR." *System Dynamics Review* 10 (2–3): 245–256. https://doi.org/10.1002/sdr.4260100211.

Geels, F. W. 2004. "From Sectoral Systems of Innovation to Socio-Technical Systems: Insights about Dynamics and Change from Sociology and Institutional Theory." *Research Policy* 33 (6–7): 897–920. https://doi.org/10.1016/j.respol.2004.01.015.

Hedström, P. 2005. *Dissecting the Social. On the Principles of Analytical Sociology.* Cambridge: Cambridge University Press.

Hekkenberg, R., and J. Liu. 2017. "Developments in Inland Waterway Vessels." In *Inland Waterway Transport*, edited by B. Wiegmans and R. Konings, 142–167. London: Routledge.

Hjorth, P., and A. Bagheri. 2006. "Navigating towards Sustainable Development: A System Dynamics Approach." *Futures* 38 (1): 74–92. https://doi.org/10.1016/j.futures.2005.04.005.

Hou, L., and H. Geerlings. 2016. "Dynamics in Sustainable Port and Hinterland Operations: A Conceptual Framework and Simulation of Sustainability Measures and Their Effectiveness, Based on an Application to the Port of Shanghai." *Journal of Cleaner Production* 135:449–456. https://doi.org/10.1016/j.jclepro.2016.06.134.

Jiang, Y., J. Lu, Y. Cai, and Q. Zeng. 2018. "Analysis of the Impacts of Different Modes of Governance on Inland Waterway Transport Development on the Pearl River: The Yangtze River Mode vs. the Pearl River Mode." *Journal of Transport Geography* 71:235–252. https://doi.org/10.1016/j.jtrangeo.2017.09.010.

Karaarslan, S., and M. Quispel. 2021. *Study on Financing the Energy Transition Towards a Zero-Emission European IWT sector.*

Kennisinstituut voor Mobiliteitsbeleid. 2021. *Mobiliteitsbeeld 2021 [Mobility Outlook 2021]*.

Kirichek, A., J. Pruyn, B. Atasoy, R. R. Negenborn, R. Zuidwijk, J. H. R. van Duin, K. Tachi, and M. van Koningsveld. 2023. "Paving the Way Towards Zero-Emission and Robust Inland Shipping." *Proceedings of MOSES 2023 Conference TU Delft Open Publishing*. https://doi.org/10.59490/moses.2023.675.

Lara, D. V. R., P. Pfaffenbichler, and A. N. Rodrigues da Silva. 2023. "Modeling the Resilience of Urban Mobility When Exposed to the COVID-19 Pandemic: A Qualitative System Dynamics Approach." *Sustainable Cities and Society* 91:e104411. https://doi.org/10.1016/j.scs.2023.104411.

Linzenich, A., D. Bongartz, K. Arning, and M. Ziefle. 2023. "What's in My Fuel Tank? Insights into Beliefs and Preferences for e-Fuels and Biofuels." *Energy, Sustainability and Society* 13: Article 35. https://doi.org/10.1186/s13705-023-00412-5.

Maraš, V. 2017. "Policies for Inland Waterway Transport: Needs and Perspectives." In *Inland Waterway Transport*, edited by B. Wiegmans and R. Konings, 188–217. Abingdon: Routledge.

Meadows, D. H., and D. Wright. 2008. *Thinking in Systems: A Primer*. New York: Chelsea Green Publishing.

Nieuwsblad Transport. 2025, March 5. *Adverteren*. https://www.nt.nl/service/adverteren/.

Pel, B. 2022. "A Transition Theory Perspective on Transport Innovation." In *Innovations in Transport*, edited by B. van Wee, J. A. Annema, and J. Köler, 14–34. Cheltenham: Edward Elgar Publishing Limited.

Perčić, M., N. Vladimir, and A. Fan. 2021. "Techno-economic Assessment of Alternative Marine Fuels for Inland Shipping in Croatia." *Renewable and Sustainable Energy Reviews* 148: 111363. https://doi.org/10.1016/j.rser.2021.111363.

Rhee, Y. P. 2000. "Complex Systems Approach to the Study of Politics." *Systems Research and Behavioral Science* 17 (6): 487–491. https://doi.org/10.1002/1099-1743(200011/12)17:6<487::AID-SRES350>3.0.CO;2-E.

Roso, V., C. A. Vural, A. Abrahamsson, M. Engström, S. Rogerson, and V. Santén. 2020. "Drivers and Barriers for Inland Waterway Transportation." *Operations and Supply Chain Management: An International Journal* 13 (4): 406–417. https://doi.org/10.31387/oscm0430280

Sterman, J. D. 1994. "Learning in and about Complex Systems." *System Dynamics Review* 10 (2–3): 291–330. https://doi.org/10.1002/sdr.4260100214.

Sterman, J. D. 2002. *System Dynamics: Systems Thinking and Modeling for a Complex World*.

Temenos, C., A. Nikolaeva, T. Schwanen, T. Cresswell, F. Sengers, M. Watson, and M. Sheller. 2017. "Ideas in Motion: Theorizing Mobility Transitions an Interdisciplinary Conversation." *Transfers* 7 (1): 113–129. https://doi.org/10.3167/TRANS.2017.070109.

Tomoaia-Cotisel, A., S. D. Allen, H. Kim, D. Andersen, and Z. Chalabi. 2022. "Rigorously Interpreted Quotation Analysis for Evaluating Causal Loop Diagrams in Late-Stage Conceptualization." *System Dynamics Review* 38 (1): 41–80. https://doi.org/10.1002/sdr.1701.

Tsakalidis, A., M. van Balen, K. Gkoumas, and F. Pekar. 2020. "Catalyzing Sustainable Transport Innovation through Policy Support and Monitoring: The Case of TRIMIS and the European Green Deal." *Sustainability (Switzerland)* 12 (8): 3171. https://doi.org/10.3390/SU12083171.

Tziva, M., S. O. Negro, A. Kalfagianni, and M. P. Hekkert. 2020. "Understanding the Protein Transition: The Rise of Plant-Based Meat Substitutes." *Environmental Innovation and Societal Transitions* 35:217–231. https://doi.org/10.1016/j.eist.2019.09.004.

Van Geenhuizen, M., and P. Nijkamp. 2003. "Coping with Uncertainty; an Expedition in the Field of new Transport Technology." *Transportation Planning and Technology* 26 (6): 449–467. https://doi.org/10.1080/0308106032000167355.

van Wee, B., J. A. Annema, and J. Köhler. 2022. "Introduction to Innovations in Transport." In *Innovations in Transport*, edited by B. van Wee, J. A. Annema, and J. Köhler, 1–12. Cheltenham: Edward Elgar Publishing Limited.

Verberght, E. 2020. *Innovation in Inland Navigation Failure and Success: The European Case*. Antwerp: University of Antwerp.

Wiegmans, B., and R. Konings. 2017. *Inland Waterway Transport*. Abingdon: Routledge.

Yao, A. F., M. Sèbe, L. R. Virto, A. Nassiri, and H. Dumez. 2024. "The Effect of LNG Bunkering on Port Competitiveness Using Multilevel Data Analysis." *Transportation Research Part D: Transport and Environment* 132: e104240. https://doi.org/10.1016/j.trd.2024.104240.

Yearworth, M., and L. White. 2013. "The Uses of Qualitative Data in Multimethodology: Developing Causal Loop Diagrams during the Coding Process." *European Journal of Operational Research* 231 (1): 151–161. https://doi.org/10.1016/j.ejor.2013.05.002.

Zero Emission Services. 2021. *ZES System*. https://zeroemissionservices.nl/en/zes-system-2/.