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North Sea Energy 2023-2025

Navigating Systematic Barriers and Enablers of the Dutch Offshore Wind Transition

Navigating the North Sea transition!

For centuries, the North Sea has been a source of economic strength, ecological richness, and international cooperation. Always subject to change, yet steadfast as a connector of nations, cultures, and economies. Today, it once again takes center stage—this time as a lighthouse region for the transition to a sustainable, affordable, and reliable energy system. The North Sea Energy program marks an important step in this development.

North Sea Energy is a dynamic research program centered around an integrated approach to the offshore energy system. Its aim is to identify and assess opportunities for synergies between multiple low-carbon energy developments at sea: offshore wind, marine energy, carbon capture and storage (CCS), natural gas, and hydrogen. At the same time, the program seeks to strengthen the carrying capacity of our economy, society, and nature.

The offshore energy transition is approached from various perspectives: technical, ecological, societal, legal, regulatory, and economic. Our publications provide an overview of the strategies, innovations, and collaborations shaping the energy future of the North Sea. They reflect the joint efforts of companies, researchers, and societal partners who believe in the unique potential of this region as a hub for renewable energy and innovation.

What makes this program truly distinctive is not only its scale or ambition, but above all the recognition that we are operating in a dynamic field of research. The energy transition is not a fixed path, but a continuous process of learning, adapting, and evolving. New technologies, a dynamic natural environment, shifting policy frameworks, and changing societal insights demand flexibility and vision. Within this program, we work together to ensure that science and practice reinforce one another.

This publication is one of the results of more than two years of intensive research, involving over forty (inter)national partners. This collaboration has led to valuable insights and concrete proposals for the future of the energy system in and around the North Sea. All publications and supporting data are available at: https://north-sea-energy.eu/en/results/

We are deeply grateful to all those who contributed to the realization of this program. In particular, we thank our consortium partners, the funding body TKI New Gas, the members of the sounding board, the stakeholders, and the engaged public who actively participated in webinars and workshops. Their input, questions, and insights have enriched and guided the program.

At a time when energy security, climate responsibility, and affordability are becoming increasingly urgent, this work offers valuable insights for a broad audience—from policymakers and professionals to interested citizens. The challenges are great, but the opportunities are even greater. The North Sea, a lasting source of energy, is now becoming a symbol of sustainable progress.

With these publications, we conclude an important phase and look ahead with confidence to the next phase of the North Sea Energy program. In this new phase, special attention will be given to spatial planning in the North Sea, European cooperation, and the growing importance of security in the energy system of the future.

North Sea Energy
offshore system integration

D2.4

North Sea Energy 2023-2025

Navigating Systematic Barriers and Enablers of the Dutch Offshore Wind Transition

Authors:

Eindhoven University of Technology
Ivo Wakounig

Radboud University
Vincent de Gooyert

Approved by:

TNO
Madelaine Halter

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Contents

Abstract

The Netherlands aims to deploy up to 70 GW of offshore wind by 2050. As one of the busiest sea area in the world, the Dutch part of the North Sea faces spatial tensions and a degraded state of nature due to activities such as fossil fuel extraction, shipping and fishing. The interconnectedness of sectors and actors makes for a highly complex situation and the further development of spatially demanding offshore wind will have substantial and various consequences, both intended and unintended. We use systems thinking to explore barriers and enablers in the Dutch offshore wind transition. We interview 22 stakeholders, organise one structured focus group discussion, and four follow-up workshops. Earlier literature focuses on single system analyses, such as the techno-economics or spatial impacts of offshore wind. Through our systems thinking approach, we elucidate on the interrelations between different sectors and activities in the domains of the socio-technical systems of offshore wind, spatial competition, and quality of nature, thereby broadening the scope of analysis. This allowed us to improve the understanding of the complexity of the Dutch offshore wind transition, helping navigate the various interrelated interests and advancing the transition. Our analysis stresses the importance of energy demand on land and the deliberate reduction of human activities in the North Sea. We conclude that the offshore wind transition can be accelerated through (i) collaborative governance; (ii) ecosystem based planning; and (iii) an energy system transformation. Our results are relevant for other countries with seacoasts aiming to deploy offshore wind.

1 Introduction

The North Sea will play an important role in the European Union's (EU) ambition to reach net-zero greenhouse gas emissions by 2050 (EC, 2021). In a memorandum of understanding with the United Kingdom, the North Seas Energy Cooperation (NSEC, 2016) pledged to deploy up to 300 GW of offshore wind capacity in the North Sea by 2050 (NSEC, 2022), out of which 70GW shall be deployed in the Dutch exclusive economic zone (Rijksoverheid, 2022). Offshore wind capacity in the Netherlands would increase by about a factor of 15 from 4.7 GW in 2024 (Wind op zee, n.d.) within 26 years, which will impact the spatial tensions in the North Sea.

The Dutch North Sea is intensively used by different stakeholders, each having their own impact and pursuing their own interests. The Netherlands harbours vast fossil fuel infrastructure in its waters, such as oil & gas wells and pipelines (Vleuten, 2010). Fishing contributes to North Sea countries' food supply, is a relevant economic activity and is part of the Dutch cultural heritage. Additionally, the North Sea is an important habitat for marine life and seabirds. Combined, human activities lead to various issues such as greenhouse gas emissions, noise, chemical pollution, and spatial tensions, leading to a deteriorated state of biodiversity (OSPAR, 2023).

The different activities are not independent from each other and can be aligned, for example oil extraction providing the fuel for ships, and misaligned, such as static oil & gas infrastructure inhibiting the mobility of traditionally mobile fisheries. With offshore wind requiring an increasing spatial share in the future, these relationships will be impacted, for example because the extent of different activities will change. The already existing tensions between the different stakeholder groups will likely be aggravated through the introduction of large scale offshore wind, leading to a variety of barriers and enablers to the offshore wind energy transition.

We align with systems thinking literature (De Gooyert et al., 2016; Williams et al., 2017), arguing that understanding and responding to such an increased use of the North Sea requires an approach which takes into account the different interactions from the start through systems thinking. Systems thinking appreciates the connectedness of different components and variables of socio-technical systems, helping understand their behaviour and modifying system's structure (Arnold and Wade, 2015). Systems thinking is an approach which embraces relationships between different activities and transcends attempts to treat apparent problems in a simplistic cause-effect approach (Abson et al., 2017; Voulvoulis et al., 2022; Williams et al., 2017).

In this research, we explore the barriers and enablers of the offshore wind transition in the Netherlands using systems thinking. In the following section we outline the context of the Dutch offshore wind transition, which is shaped by connectedness and dependencies between different stakeholder groups. The stakeholders in the North Sea have different interests and mental models, which can be surfaced by causal loop diagrams developed in group model building workshops (Hovmand, 2014). This approach will be explained in section 0, alongside the methodology. In section 0 we present the models which help us identify barriers and enablers to the offshore wind energy transition in the Netherlands. The results will be discussed in section 5, followed by conclusions and policy recommendations for how offshore wind deployment can be accelerated in section 6.

2 Context

The European Climate Law and the Renewable Energy Directive III stipulate that the Netherlands has to achieve net zero greenhouse gas emissions by 2050 and a share of at least 42.5% renewables in its gross final energy consumption by 2030 (EC, 2023, 2021). This will require a phase out of a majority if not all fossil assets in the Dutch North Sea and a simultaneous deployment of renewable energy, such as offshore wind. In 2024, the Netherlands had an offshore wind capacity of 4.7 GW, the most recent additions being wind farms in Borssele, Hollandse Kust Noord and Hollandse Kust Zuid (Wind op zee, n.d.). By 2032 the Netherlands aims to have an offshore wind capacity of 21 GW (EZK, 2024), and by 2050, about a quarter of the Dutch North Sea would be dedicated to an offshore wind capacity of 70GW (Matthijsen et al., 2018), signifying a large spatial footprint.

The introduction of offshore wind will not only support the replacement of fossil fuels but affect the current usage of the North Sea too, such as fishing, shipping, and marine conservation. The fossil infrastructure in the Netherlands is highly developed, for example for gas transport and distribution and with fossil industrial clusters around port areas, leading to a large spatial footprint (Vleuten, 2010). The Maritieme Monitor 2024 (Streng et al., 2024) highlights that in 2023, the maritime cluster, which consists of shipping, ports, fishing, ship building, and so forth, had an added value of around EUR 48.73 bln, contributing around 3.5% to Dutch GDP while employing around 290,000 workers. The different sectors' contribution to Dutch GDP and employment diverge greatly. For example, while shipping and offshore energy have an added value of EUR 2.41 bln and EUR 6.40 bln and employ around 7,500 and 26,750 people respectively, fishing had an added value of EUR 0.22 bln and employs around 1,760 people. Ports are another crucial sector, employing around 61,000 people and having an added value of EUR 7.28 bln. Additionally, sectors also have socio-cultural relevance. For example, while fisheries contribute less to macro-economic indicators compared to other sectors, their socio-cultural impact on coastal communities makes them an important stakeholder in the Dutch North Sea. Furthermore, fisheries use the whole North Sea as their fishing grounds and are not as confined in their activities, unlike activities such as shipping of offshore energy, which have dedicated areas allocated to them.

Marine conservation is another 'sector' which requires space. The EU Birds and Habitats Directives mandate EU member states to implement so-called Natura 2000 in their national legislation (EC, 2014), through which species are protected and restored. Seven areas in the Dutch North Sea, such as Doggerbank and the Noordzeekustzone, have been designated as Natura 2000 areas (Noordzeeloket, n.d.), resulting in around 20% of the Dutch North Sea being designated to nature protection (Vrooman et al., 2022). The recently adopted Nature Restoration Law of the EU binds member states to protect at least 30% of their land and sea areas by 2030 (EC, 2024a), causing an increase of space dedicated to nature restoration in the Dutch North Sea. The Oslo and Paris (OSPAR) Convention, adopted in 1992, regulates marine activities and their environmental impacts, such as preventing pollution and assessing the quality of marine environments in signatory states, and requires the full decommissioning of offshore installations at the end of their lifetime (OSPAR, 1992).

Put together, the decarbonisation goals of the European Climate Law and the ecological goals of the European Nature Restoration Law, all embedded within already existing frameworks, will cause significant changes in the spatial and, hence, usage profile of the Dutch North Sea. The climate and ecology ambitions operate in a geopolitical context with decision makers calling for greater energy independence and security (EC, 2024b). Given the currently existing co-dependent stakeholder landscape, these changes are expected to lead to significant tensions in the relationships between different parties. This interrelatedness of the different sectors due to spatial limitations and ecological requirements leads to a highly complex situation, which obfuscates the identification of barriers and enablers to the offshore wind transition in the Netherlands.

Our research focuses explicitly on the offshore wind ambitions in the Netherlands and the potential impacts on the existing socio-technical fabric, wherein we treat the ‘external’ developments such as geopolitical tensions as exogenous factors. In order to understand how the current and future usage of the North Sea enables and constrains offshore wind deployment, it is necessary to get an understanding of the full extent of the dynamics and the interrelatedness of the different sectors. In this research we will employ a systems thinking perspective, allowing us to analyse interdependencies between sectors and to shed light on barriers and enablers of the Dutch offshore wind energy transition.

3 Methodology

We build on system thinking and participatory research methods to identify barriers and enablers of the offshore wind transition in the Dutch North Sea. In this section, we will explain systems thinking and how we operationalise it, describe key concepts such as causal loop diagrams (CLD) and group model building (GMB), and elaborate on the research process of this study and how it connects to transitions research.

3.1 Systems Thinking as a Method

A system consists of elements which are connected which each other, achieving a certain function or purpose (Meadows, 2008). Systems thinking is about appreciating those connections and seeing them as opportunities to modify system structure to achieve desired effects (Arnold & Wade, 2015). Particularly in the context of sustainability transitions, systems thinking can be an effective tool to identify dependencies and drivers of system structures by providing a framework which transforms the way problems, desired end-states, and development pathways are identified, going beyond simplistic cause-effect approaches (Abson et al., 2017; Voulvoulis et al., 2022; Williams et al., 2017).

System dynamics is closely related to systems thinking and focuses on changes in systems over time, particularly due to systems' feedback loops (closed circles of causal relationships) and their temporal changes (Bérard, 2010; Sterman, 2001). In applied research such as ours, system dynamics modelling can improve the understanding of problems, resulting in new and practically relevant knowledge (De Gooyert and Größler, 2018). Applied system dynamics is undertaken in contexts where participants come from various backgrounds (De Gooyert and Größler, 2018). Recent system dynamics scholarship has investigated energy transition challenges in the Dutch context, for example with regards to narratives on carbon capture and storage (Janipour et al., 2021), decarbonisation strategies of a chemical cluster (Janipour et al., 2022), and effective climate policies (De Gooyert et al., 2024b). In this article, we use system dynamics as our engagement framework to develop causal loop diagrams. We do so by developing causal loop diagrams in group model building workshops.

3.1.1 Causal Loop Diagrams and Feedback Dynamics

Causal loop diagrams are one kind of system dynamics models and they show causal relations between different system components. The connections between two system components A and B can be positive or negative. Positive relationships mean that if the value of system component A increases / decreases, variable B increases / decreases too, for example an increase / decrease of GHG emissions leads to an increase / decrease of global warming. For a negative relationship, the direction of change is opposite, so if A increases / decreases, B decreases / increases, for example an increase / decrease of predators lead to an increase / decrease of prey. The connections between two variables are assumed to be 'ceteris paribus' (all else equal), which may not always be accurate but simplifies thinking in systems. Furthermore, in many cases, not only does variable A have an effect on B, but B also has an effect on A, either directly or via other variables C, D, E, and so forth. In those situations, the system components form either a reinforcing or balancing feedback loop, which has a profound impact on a system's dynamics.

Figure 1 shows the nature and impact of reinforcing (even number or no negative relationships) and balancing (uneven negative relationships) feedback loops on system parameters, their classification being non-normative. It also introduces the system dynamics notation used in this and other articles (De Gooyert et al., 2024b; Janipour et al., 2022, 2021). Reinforcing feedback loops lead to exponential growth or decline, whereas balancing feedback loops lead to oscillation around / towards a certain value. Reinforcing feedback loops therefore have a double sided nature which can lead to opposite results (exponential growth or exponential decline), whereas balancing feedback loops lead to goal seeking behaviour through convergence (Meadows, 2008). In real systems, variables are usually connected through all kinds of reinforcing and balancing feedback loops, therefore the combined effect of those feedback loops determines a variable's and a system's dynamics.

In our research we construct causal loop diagrams through a group model building workshop and follow-up workshops, based on which we identify feedback loops which are used to learn about barriers and enablers of the offshore wind energy transition. We focus on feedback loops because of their relevance for the development of the offshore wind transition. Balancing feedback loops are typically sources of stability and inertia, so that reducing inertia becomes a matter of reducing the dominance of the balancing feedback loops responsible for it. Reinforcing feedback loops are typically sources of change, so that achieving a transition becomes a matter of strengthening the reinforcing feedback loops that work in the desired direction and weakening those that work in undesired directions.

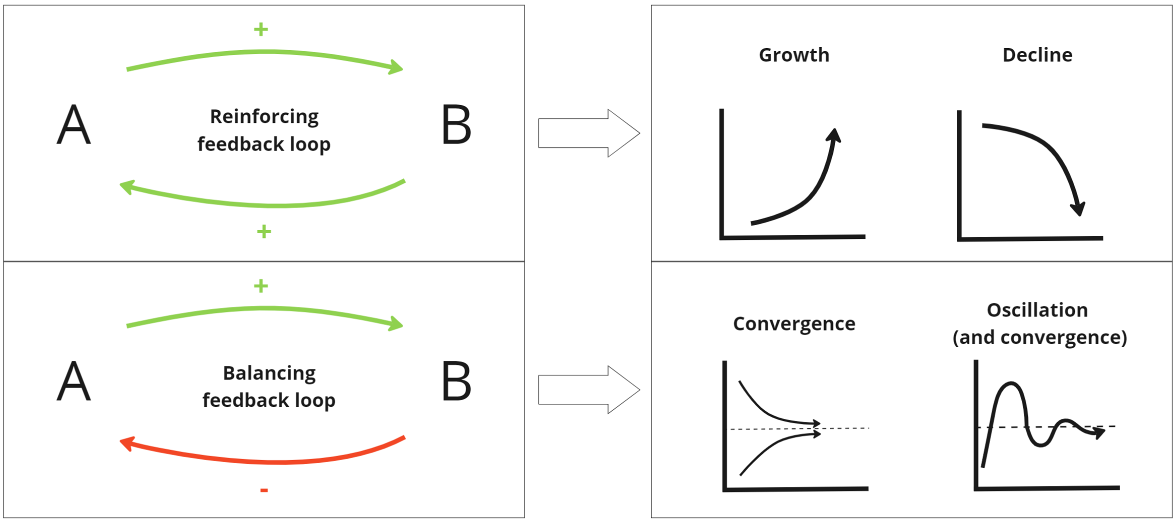

Figure 1: Impact of reinforcing and balancing feedback loops on system parameters. Reinforcing feedback loops can lead to exponential growth and decline, whereas balancing feedback loops can cause system parameters to converge to a certain value and oscillation around / towards a certain value.

3.1.2 Group Model Building as an Engagement Tool

Group Model Building (GMB) is a method which can help tackle complex problems (Vennix, 1999). As highlighted by De Gooyert et al. (2024), changing systems requires thinking and acting in systems, which can be facilitated by GMB. While many different techniques and variations exist, the fundamental approach behind GMB is that different stakeholders develop a representation of a system together in a group setting, which starts with divergent activities, followed by convergent tasks (Andersen and Richardson, 1997), while a facilitation team guides the participants through the process (Richardson and Andersen, 1995). The outcome of such an exercise is a system model, in our research a causal loop diagram (Scott, 2018). Such a system model (i) adds rigour to system analysis; (ii) supports the identification of feedback relations; (iii) explicates the understanding of a problem; and (iv) acts as memory for the participants (Vennix, 1999). Hovmand (2014) argues that the key goal of GMB is to socially construct a boundary object (Vennix, 1999), which is a CLD in our research, representing dependencies across multiple sectors and disciplines. Such a CLD acting as a boundary object helps understand the effect of those dependencies and the implications for each element in that system (Black and Andersen, 2012). GMB can build enduring agreement among research participants (Scott, 2018), because of persuasive content, structured arguments, and building trust, among other factors (Scott, 2019). Building such an agreement among participants is particularly intriguing in situations where different stakeholders, interests, and mental models clash and conflict with each other. Although system dynamics regularly includes quantitative computer simulation (De Gooyert, 2019), in this study we use qualitative system dynamics because of its broad scope and exploratory nature, which comes with many uncertain and hard to quantify socio-technical elements (De Gooyert et al., 2024a). Our focus was to learn about the system with the research participants and to identify barriers and enablers by building on the insights from relevant stakeholders in the Dutch North Sea. In the following we will describe the research process which led to the development of CLDs and the identification of barriers and enablers.

3.2 Research Process

The research process is illustrated in Figure 2. After identifying offshore wind expansion in the Dutch North Sea as the research problem, a literature review led to the formulation of the research question, which was accompanied by identifying and reaching out to relevant stakeholders. We embed our work in transitions research, which highlights the multi-layered nature of transition processes of socio-technical system (Geels, 2002), the connectedness between technologies and societies (Geels, 2004; Rotmans and Loorbach, 2009), and transitions' normative direction, uncertainty and emergence, and stability and change (Köhler et al., 2019). Through that we appreciate the connections between different stakeholders and sectors, and technologies' socio-cultural embeddedness. Throughout the research process there was a constant iteration with the qualitative data collection through interviews and workshops, indicated by the dashed lines in Figure 2. Our initial stakeholder mapping was derived from policy related and grey literature, and interactions with participants of the North Sea Energy (NSE, n.d.) research programme, which explores energy system integration options in the North Sea. The stakeholder groups identified in this initial mapping included energy companies, utilities, fisheries, grid operators, ports, shipping companies, nature organisations, policy makers, marine contractors, consultancies, and activist groups. We recruited research participants via the network of the NSE research programme, participation at energy related events in the Netherlands, and contacting organisations via their websites and LinkedIn. These stakeholders participated in the subsequent interviews, group model building workshop, and follow-up workshops. The number of participants per research steps can be found in Table 1.

We conducted 22 preparatory interviews from June to August 2024. The interviews' themes were (i) interviewees' understanding of system dynamics in the North Sea; (ii) problem definition of the status quo; (iii) future vision; and (iv) additional comments. The guide can be found in Annex A and the interviews were conducted in a semi-structured manner for around 45 minutes each. The questionnaires were informed by literature and tailored to participants' background and expertise. Four interviewees asked to avoid that certain statements can be attributed to their organisation, therefore we chose to pseudonymise interview data and we will not attribute statements to different sectors. This reduces the transparency of the analysis, however, it allows interviewees to share their perspectives more freely. The interview transcripts were analysed using grounded theory (Timonen et al., 2018), facilitated by the software NVivo (Lumivero, n.d.). The mother codes developed through this process include (i) external influences: (ii) North Sea here and now; (iii) physical conditions of the North Sea; (iv) politics & policy; (v) sectors; (vi) transformation; and (vii) understanding of an energy system, each but the latter with their own daughter codes. Throughout the coding process the codes were corroborated by connecting them to relevant literature from the review. Through the interviews it became apparent that additional sectors in the Dutch North Sea include tourism & recreation, storage, sand extraction & mining, and military, out of which only the latter interviewees' framed as relevant. However, recruiting research participants from the military sector has been unsuccessful, same with shipping companies.

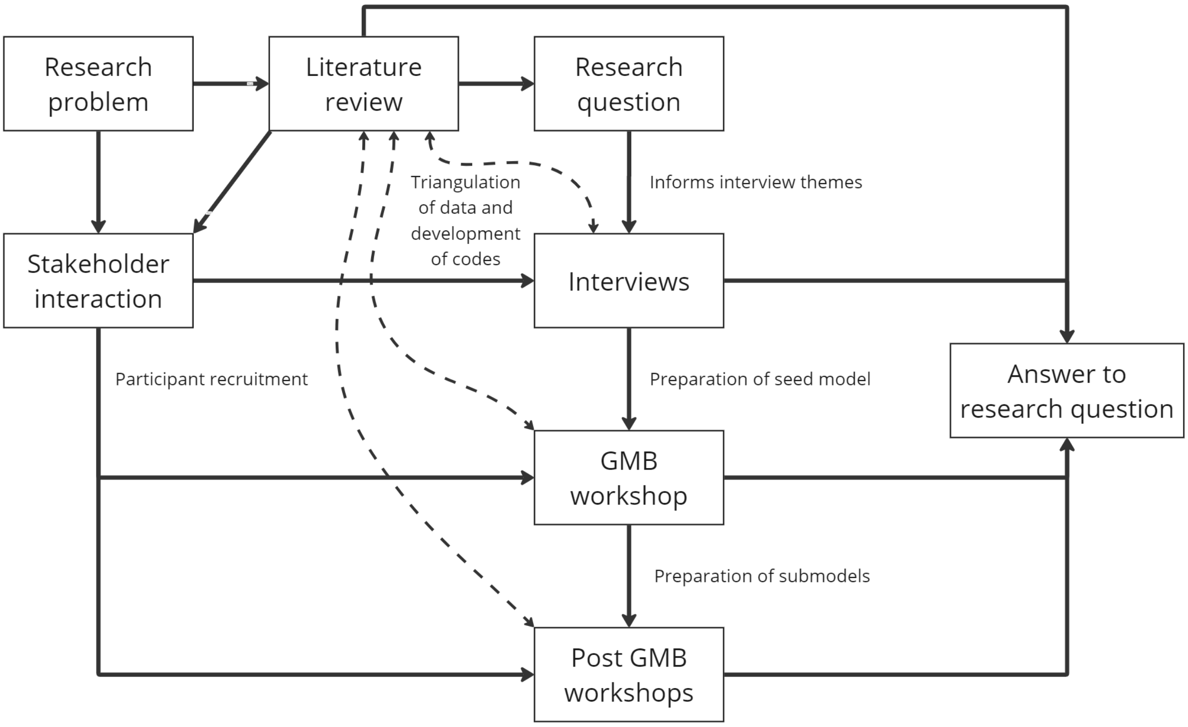

Figure 2: Illustration of the research process based on the description in the text and inspired by De Gooyert et al. (2024). The dashed lines stand for continuous processes to triangulate data and inform subsequent research steps with relevant literature.

Table 1: Number of participants per sector per research step. Many participants took part in multiple research steps. The number in the brackets for the columns 'GMB' and 'Post GMB Workshops' indicates how many new participants joined in this research step. In total, 30 individuals took part in this research. One of the post GMB workshops took place during a review meeting of the research programme and it was not possible to record the sectors of the participants, hence, the 'true' number of participants is slightly higher.

Sector	Interview	GMB	Post GMB Workshops	Unique participants
Energy & grids	10	2 (0)	3 (0)	10
Ports	3	1 (0)	2 (1)	4
Contractors & Consultancy	2	3 (1)	2 (0)	3
Ministries	2	0 (0)	0 (0)	2
Research	1	3 (3)	1 (1)	5
Environmental organisation	2	1 (0)	3 (2)	4
Fisheries	2	2 (0)	1 (0)	2
Sum	**22**	**12 (4)**	**12 (4)**	**30**

Through the interviews and the codes we gained an overview of the relevant issues in the Dutch North Sea in connection with the deployment of 70GW of offshore wind until 2050, as well as sectoral perspectives about its impact on their operations. The interviews also led to the construction of a so-called seed model (Handel and Kleemann, 2016), which was the starting point of the GMB workshop in September 2024 and was expanded in it. This seed model can be found in Figure 3 and it shows the simplest representation which mirrors emerging themes during the interviews, including the growing offshore wind capacity, its spatial requirements, as well as the impact of spatial rearrangements on fisheries and nature.

Figure 3: Seed model which was developed for the GMB workshop, based on key themes in the preparatory interviews.

The GMB has been conducted early September 2024 and included 12 participants (see Table 1). Eight participants took part in the prior interviews, whereas the other four participants joined anew. The workshop was facilitated by the two authors and the participants built the CLD together. In total, the workshop lasted around five hours, including breaks, and consisted of divergent and convergent activities. For these activities we relied on commonly used facilitation scripts such as variable elicitation, round robin discussion, extending the seed model, and model review (Wikibooks, n.d.). We refined the model which was generated after the workshop to increase its readability, and we added some connections which were missing to ensure logical sequences. Furthermore, we cut the model into smaller submodels based on the importance of certain variables in the model (number of connections) and the interview codes. In total, we identified six themes as well as their respective submodels. We used those submodels in the further research and they were sent to the participants for their comments. Three participants commented on the model results, however, they didn't lead to changes in the model structure but rather to more interpretative context in the analysis.

The final step in the empirical analysis consisted of follow-up workshops with a subsection of stakeholders. The rationale for bringing different stakeholder groups together, rather than all sectors, was to dive deeper into selected submodels and focus on the biggest point of conflict between those stakeholder groups. This allowed for more nuanced interpretation of the models with the stakeholders. Furthermore, this step was to go beyond constructing a causal loop diagram and to also use the models to identify barriers and enablers. We organised four workshops of 2.5 hours with 3 – 5 participants each, their profile being shown in Table 1, and an additional, shorter workshop has been held during a review meeting of the NSE research programme. During those workshops, participants were invited to comment on the submodels and modify the connections. Furthermore, we asked participants to share their perspectives on desired and undesired impacts of relevant submodels on their sectors, list barriers and enablers to the offshore wind energy transition in the Netherlands, and suggest policy interventions which should either support the desired or help mitigate the undesired impact. The post GMB workshops showed that themes kept re-appearing during the discussion of the different submodels, therefore not all submodels were useful in elucidating new insights in the system's dynamics.

As a result, in the final step, instead of analysing all six submodels, we focused on the three most relevant submodels. We assessed their relevance based on the interview codes and participants' response during the workshop, the main themes being offshore wind capacity, spatial competition, and quality of nature. We identified feedback loops using Vensim (Ventana Systems, n.d.). We summarised feedback loops with similar causal mechanisms as one and highlighted them with a star symbol in the causal loop diagrams. Finally, barriers and enablers were elucidated by the participants using the feedback loops in the models. Our policy recommendations at the end of this article build on the feedback relationships and participants' suggestions based on the participative analysis.

4 Results

In this section, first, we will present the three submodels in depth without a particular order. This is followed by the presentation of barriers and enablers for offshore wind deployment in the Dutch North Sea.

4.1 Causal Loop Diagrams of the Submodels

In this section we present the three submodels which have been developed in our research through GMB and follow-up workshops (Figure 2). These submodels are about the (i) techno-economics and socio-politics of offshore wind capacity; (ii) change dynamics of spatial competition; and (iii) goal seeking behaviour of quality of nature. For each of the submodels we elaborate on the connections and feedback loops, and connect some to participants' views and statements. The explanations of the feedback loops, the three other submodels which have been a result of the GMB and used during the follow-up workshops, and the complete model can be found in Annex B and C. The implications of these models are contextualised in section 4.2.

4.1.1 Techno-Economics and Socio-Politics of Offshore Wind Capacity

The CLD for offshore wind capacity can be found in Figure 4. Offshore wind capacity is subject to a variety of different feedback mechanisms, broadly located in the themes of techno-economics of infrastructure (B1*, B2*, R1*), socio-politics in the form of public acceptance (R2*, R3, B4, B5), and the desire to deploy offshore wind (all feedback loops), all of which are intrinsically interconnected. In that context, all interviewees raised concerns about whether 70 GW offshore wind capacity can be deployed by 2050, for example because the 'timelines are not so realistic' (participant 18), there 'will be a shortage in the supply chain' (participant 14), and its ecological impact would be too severe. Below we will dive deeper into each of the themes to provide a more detailed analysis of the dynamics.

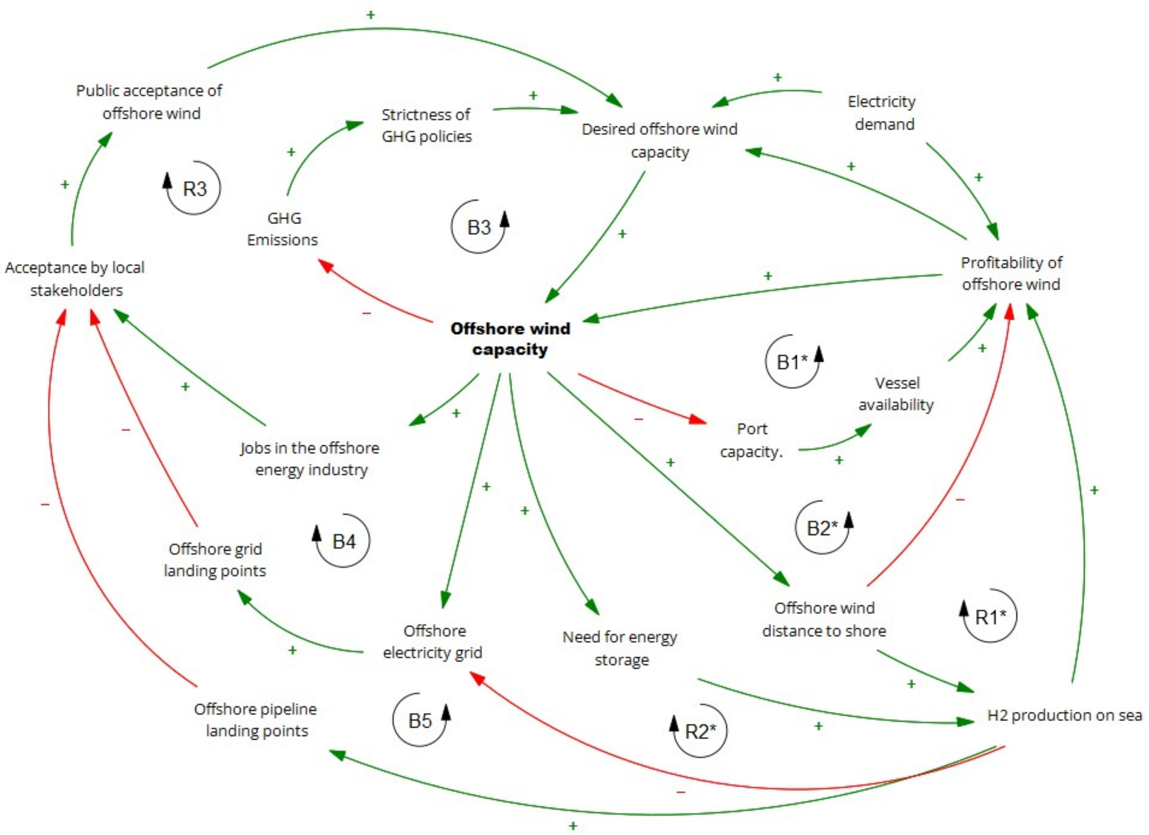

Figure 4: CLD of offshore wind capacity. Feedback loops denoted with a star summarise two or more feedback loops taking a similar route, reflecting a similar causal mechanism. The descriptions for the different feedback loops can be found in Annex D.

The techno-economics of offshore wind is strongly driven by the ability to absorb the energy produced and the supply chain, all of which feed into the profitability of offshore wind. Due to its intermittent nature, higher levels of offshore wind capacity face energy system integration challenges. For example, participant 23 is sceptical whether the infrastructure is ready for 70GW of offshore wind, because '…the grid is flooded with so many green electrons that we can't use it'. This emphasises the need to create energy demand, transmission infrastructure, and storage, for example batteries and (offshore) hydrogen.

Most participants are more positive towards (offshore) hydrogen as an integration vector. Despite its economic challenges, offshore wind coupled with hydrogen production can lead to economies of scale, where further offshore wind and hydrogen deployment go in tandem (R1*), thereby improving its profitability. Hydrogen would serve as an energy storage vector and increase profitability when offshore wind farms are deployed further offshore (B2*). Common arguments for offshore hydrogen production are that already existing fossil infrastructure could be re-used, for example by repurposing the fossil gas grid, that pipelines are cheaper than electricity cables, and that hydrogen could be used in the industrial (port) areas in the Netherlands and as a new export product for the industrial centres in North-West Europe. However, feedback loop R1* also indicates that the deployment of offshore wind is contingent on its profitability, without which developers wouldn't commit to building the necessary infrastructure. The profitability of offshore wind is largely determined by the electricity demand (on land), meaning that without parallel electrification of residential and industrial energy demand the profitability of offshore wind could suffer.

A key issue in the growth of offshore wind lies in its supply chain, for example ports and vessel availability (B1*). Construction, operations and maintenance of offshore wind farms affect port infrastructures and increase maritime traffic. One particular issue for supply chains is innovation in turbines sizes, which, according to participant 8, is 'humongous' and requires entirely different port and vessel infrastructure. Furthermore, different bids often have different turbine sizes, resulting in the construction of a separate installation infrastructure for each project.

The extent of the infrastructure feeds into the theme of public acceptance of infrastructure. Offshore wind and potential hydrogen infrastructure will be visible in coastal areas, for example because of the landing points, which can lead to reduced acceptance of local stakeholders, ultimately undermining the popular support for offshore wind deployment (B4, B5). However, hydrogen production can reduce overall infrastructure requirements close to shore by reducing the extent of electricity grid infrastructure and thereby reduce the burden on residents (R2*). The public mandate for offshore wind deployment in the North Sea can depend on how local communities are impacted. Jobs in the offshore wind industry can increase public acceptance if local or coastal communities can work in the sector (R3). Finally, according to some participants, the impact on the fishing industry from offshore wind deployment can strongly affect local communities, because of jobs losses in the fisheries sector as well as a potential loss of socio-cultural value linked to the fishing industry.
The techno-economics and public acceptance of offshore wind are highly interconnected through grid infrastructure, affecting the desired offshore wind capacity. The techno-economics affect the desirability through profitability concerns, whereas the public acceptance affect it through the way society responds to this infrastructure. While large deployment of infrastructure can positively impact the business case of offshore wind, it can undermine public support and, ultimately, desired offshore wind capacity. All the time the need to reduce GHG emissions driving the desired offshore wind capacity (B3). Hence, offshore wind capacity is affected by multiple, interconnected themes.

4.1.2 Change Dynamics of Spatial Competition

Figure 5 shows the CLD for spatial competition. As one of the most intensively used sea areas in the world, the Dutch North Sea's spatial competition will experience significant changes with the introduction of spatially demanding offshore wind. The spatial impacts of offshore wind expansion are located in the themes of multi-use of space (R5, R6*), port capacity and nature impact (B6*, B7*), and energy infrastructure (R4). Below we explore the dynamics in those themes.

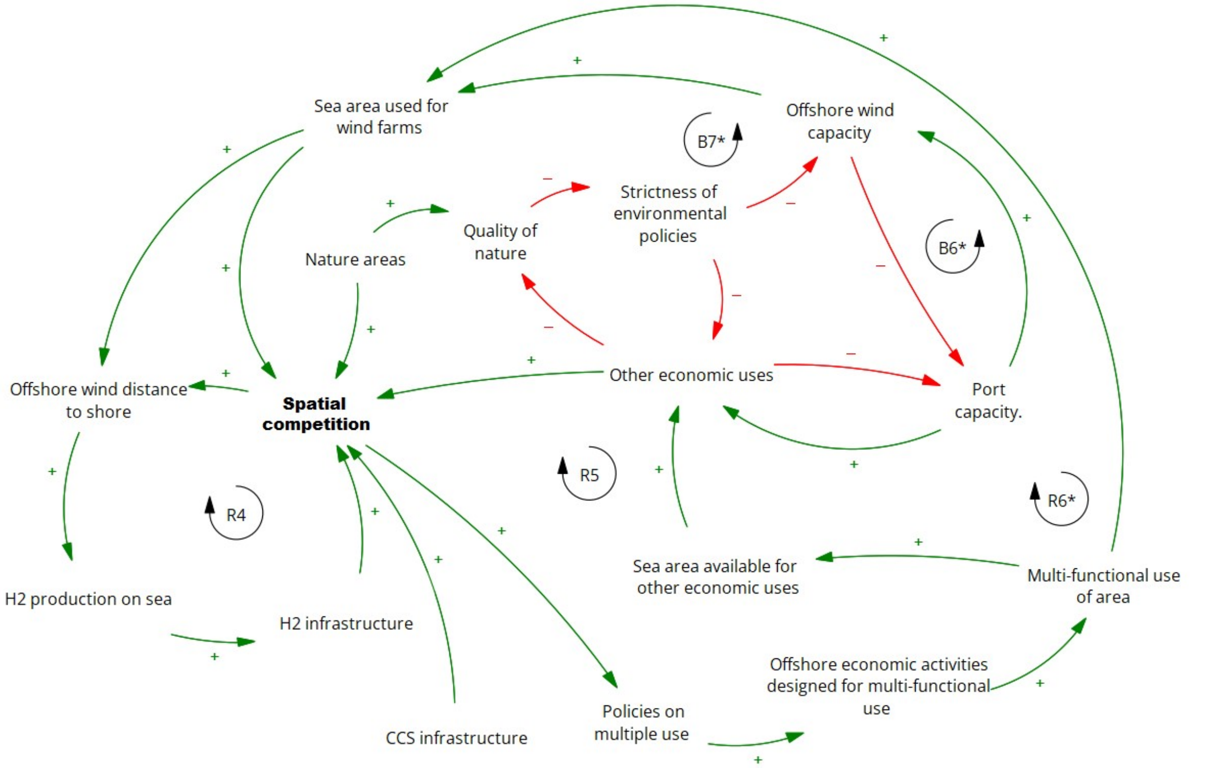

Figure 5: CLD of spatial competition. Feedback loops denoted with a star summarise two or more feedback loops taking a similar route, reflecting the same causal mechanism. The descriptions for the different feedback loops can be found in Annex D.

Due to the scarcity of space, multi-use has been mentioned as a potential solution to use space more efficiently by pursuing more activities in the same area, for example by using offshore wind areas for passive fishing. However, the CLD on spatial competition shows that multi-functional use policies can lead to higher spatial competition (R5) as they can increase the spatial usage of the North Sea within and outside multi-use areas. As participant 3 says, most activities keep growing and 'multi-use is really primarily about doing more things in the same space', while participant 5 says that despite its attractiveness, 'the real interest in co-use is not so big', because it leads to more conflicts in multi-use areas and it raises insurance concerns. Furthermore, since multi-functional use would provide more available sea area to offshore wind, it can lead to higher spatial pressure arising from offshore wind infrastructure (R6*).

Port capacity and quality of nature serve as balancing factors of all activities in the North Sea. Ports are the gateways between land and sea and all activities rely on port capacity to function effectively, so offshore wind too (B6*). Quality of nature is affected by how effective environmental policies can regulate economic uses and reduce their negative impact on nature, affecting the (legally) deployable amount of offshore wind (B7*). Due to the limited (physical and ecological) space and the growing activities, it is about making choices which activities will get areas allocated to them. Many participants struggle to see how the different uses can be combined. Fisheries are expected to be the sector whose spatial share will go down the most. Stakeholders from the fishing industry argue that less space will be allocated to fisheries because other sectors have a stronger political leverage and more influence on policy making. Finally, many participants acknowledge that the spatial pressure and the re-arrangement of sectoral shares forces sectors to think about their future role and how they can transition.

The growth of energy (related) infrastructure is another key theme emerging from this CLD. Higher offshore wind capacity will push wind parks further offshore, leading to higher system integration needs and spatial requirements arising from this infrastructure (R4). Furthermore, potential carbon capture and storage (CCS) infrastructure would add to spatial competition.

Similar to offshore wind capacity, the CLD for spatial competition highlights the strong interdependency between the different factors and activities in the North Sea, driving spatial competition. This model shows that the introduction of offshore wind capacity will add to the already existing spatial contestation in the North Sea, and solutions such as multi-use of sea areas and energy system integration infrastructure in the form of hydrogen would increase the spatial demand, indicating a rebound effect. Realising multi-use potential in practice is a challenge, contingent on how the tensions with the already existing users can be resolved. Port capacity and quality of nature (and the corresponding regulations) serve as balancing factors, making them serve as ceilings for the activities, which are taking place in the North Sea.

4.1.3 Goal Seeking Behaviour of Quality of Nature

The CLD for quality of nature is shown in Figure 6. Quality of nature, synonymous for a thriving flora, fauna, and their habitats, is linked to the above challenges and is affected by human activities in different ways. The main themes for the effects are changes in habitat (B10, B11), effects on marine and non-marine populations (R7, B12), and the role of environmental policies (B8, B9). These three themes are explained in greater detail below.

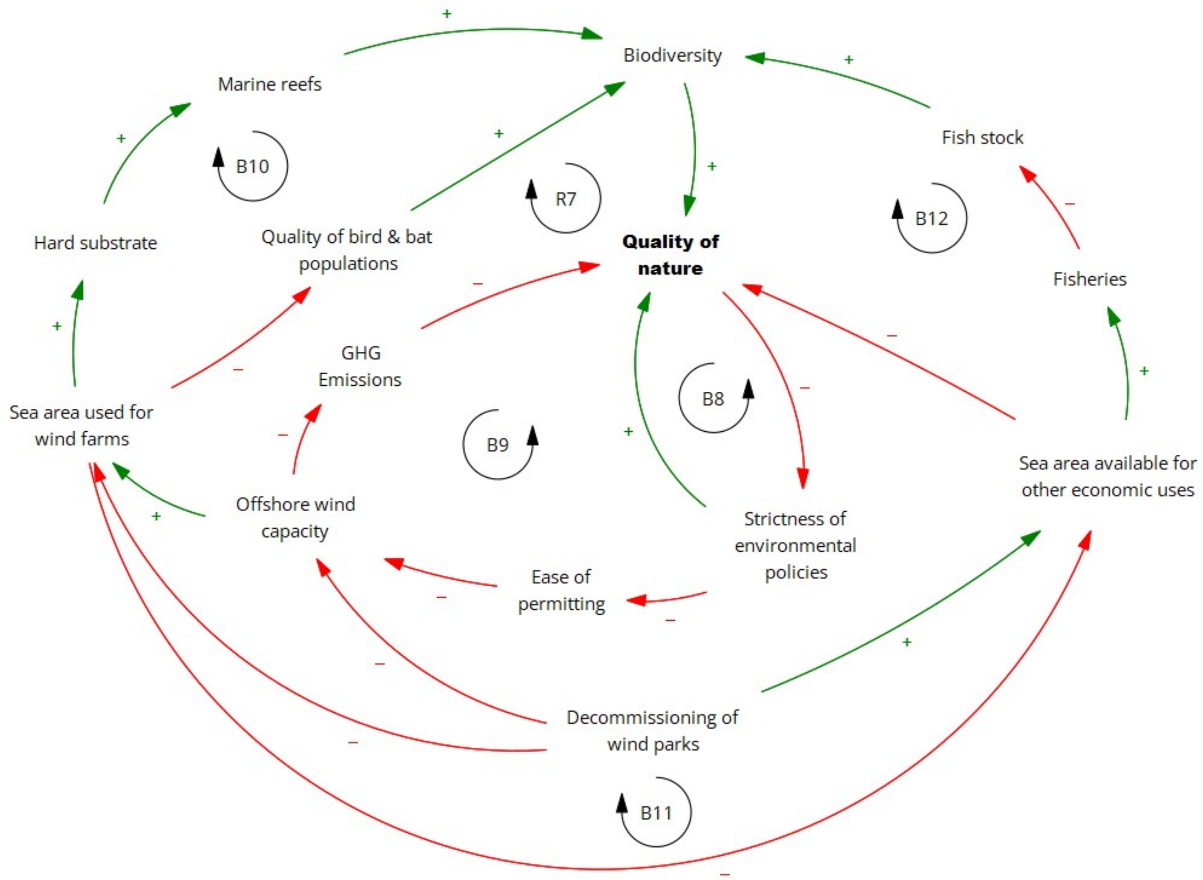

Figure 6: CLD of quality of nature. The descriptions for the different feedback loops can be found in Annex D.

The impact of offshore wind on habitats is diverse. For example, offshore wind infrastructure leads to higher levels of hard substrate and marine reefs, positively affecting quality of nature (B10), and generally, higher levels of offshore wind increase the creation of such habitats. However, this only comes into effect a few years after installation of offshore wind turbines and the installation of the monopiles itself can have severe short-term negative effects on the seabed due to noise emissions and physical changes. Once offshore wind farms and its associated infrastructure have to be decommissioned at the end of their lifetime, their positive effect would disappear. Habitats are also changed when offshore wind farms displace other economic sectors (B11), which mostly have negative impacts on biodiversity.

The impact of offshore wind and other activities on marine and non-marine populations highly impacts quality of nature. On the one hand, the introduction of offshore wind has a detrimental impact on bird and bat populations, for example through avoidance, collisions, and barrier effects (R7). On the other hand, by displacing active fisheries, fish stock is positively influenced, causing a goal seeking behaviour of quality of nature through offshore wind capacity (B12).

Another important component affecting quality of nature are environmental policies. Environmental policies affect the impact human activities will have on nature, and their strictness depends the quality of nature, making it converge to a level which is in line with policy ambitions (B8). Furthermore, even though offshore wind can reduce GHG emissions and thereby improve the quality of nature, the amount of offshore wind will depend on nature's carrying capacity and the level to which environmental policies can regulate activities (B9).

Overall, this CLD shows that quality of nature exerts a strong goal seeking behaviour, wherein biodiversity adapts to the activities taking place in the Dutch North Sea. According to participant 12, offshore wind infrastructure is 'quite a significant alternation of the system'. It leads to changes in ecosystems, species interaction, and, in worst cases, complete loss of habitat. Participant 18, even though underlining that offshore wind is a good choice, is 'not sure if it's sustainable'. Furthermore, the human-made infrastructure is still an artificial one, and even though it may promote marine growth, it does not mean that the quality of nature improves, because certain types of marine species may benefit more than others. Various research participants urge that there is a lack of knowledge when it comes to the impact of offshore wind infrastructure on nature and to what extent offshore wind farms can harbour healthy ecosystems, particularly at this scale. Participant 18 emphasises that we don't know the impact of large scale offshore wind farms, and 'we only will know in 20-30 years when it's maybe already too late'. Finally, participant 10 argues that we should not strive to rebuild the North Sea ecosystems of the past but rather 'accept that a natural system is also dynamic and changes over time'.

4.2 Barriers and Enablers in the Offshore Wind Transition

The three consensus models underline that aspects such as techno-economics, infrastructure, socio-politics, space, and nature are deeply connected in the Dutch offshore wind energy transition. Due to the causal chains, interventions in some parts of the system can lead to (unintended) consequences in other parts. There are different stakeholder interests at play, for example claims over space, the pursuit of certain technological pathways, and nature protection. These different interests can clash, be aligned, or be independent from each other.

Given the various impacts offshore wind deployment has on the Dutch North Sea and the extent to which this deployment is impacted by political, natural, and social factors, in the following, we present barriers and enablers and outline how the offshore wind energy transition can be accelerated in the Dutch North Sea. We derived the barriers and enablers from the models' feedback loops and participants' views on those feedback loops during the workshops. They have been elucidated by the participants in the follow-up workshop with the help of the CLDs and they have been included on a consensus basis within the subgroups. The distinction of barriers and enablers is rather blurred as they are often sides of the same coin, particularly when reinforcing feedback loops are active. A list of the barriers and enablers can be found in Table 2 including their relationship to feedback loops. Below we present those in light of participants' views.

Barriers are the *socio-political impact of extensive electricity and hydrogen infrastructure*, *political conflict due to the displacement of other sectors*, *lack of space*, and the *state of nature*. The offshore wind goals will lead to a growth of electricity (B4) and hydrogen (B5) infrastructure, which can cause socio-political conflict, for example because people could resist the extent of the energy infrastructure. This infrastructure can lead to further political conflict by displacing other sectors in the North Sea (R4), for example because of lack of space (R5, R6*). The different activities' impact on nature and the need to protect it are important factors which can inhibit offshore wind deployment (R7, B7*).

Enablers are *energy demand*, offshore *energy hubs*, the *deliberate reduction of human activities*, and the *inclusion of coastal communities in the energy transition*. Higher residential and industrial electricity demand can lead to increased profitability of integrated offshore wind, making electrification on land a key strategy for successful offshore wind deployment. As port capacity is restricted by the availability of already scarce space on land, a potential option to facilitate vessel operations and energy system integration for higher levels of offshore wind capacity could be offshore energy hubs (B2*). Those hubs can ease logistics for other activities too and enable more efficient use of sea area through multiple-use policies. However, since this can lead to an overall increase in activities and, hence, an even stronger pressure on nature, multi-use policies should go hand in hand with activity reduction policies, wherein the cumulative effect of human activities in the North Sea is reduced (R5, R6*, B11, B12). Finally, proactively including coastal communities in decision-making processes regarding infrastructure deployment in their vicinity would be a central strategy to proactively avoid resistance of coastal communities (B4, B5, B11, B12).

Depending on the context, factors which can act as either barriers or enablers are *energy system integration*, *profitability of offshore wind*, *port capacity and the supply chain*, *local job creation*, *multiple-use*, and *environmental policies*. Energy system integration can enable offshore wind expansion when it leads to higher profitability of offshore wind and compensate the loss of profitability when offshore wind farms are placed further offshore (R1*, R2*, B2*). Likewise, it can act as a barrier when the higher levels of profitability cannot be realised (R1*), for example when the investment costs for the infrastructure are too high, when there is insufficient energy demand, and when the size of infrastructure due to the integration leads to resistance among local coastal populations (B4, B5). Port capacity and the supply chain for (integrated) offshore wind farms can be an enabler when they can service the growing infrastructure (B1*), for example by expanding ports and by investing in supply chain innovations such as drones. On the other hand, it can act as a barrier when the wider supply chain cannot keep up with growing offshore wind demand (B1*) or if higher port capacities lead to a growth of other activities because they can utilise this space too (B6*), thereby increasing spatial competition in the Nort Sea. The creation of jobs (R3) is another theme which can be a barrier, for example if local populations cannot profit from offshore wind infrastructure through employment, and an enabler, when jobs can be provided to residents, for example through dedicated job programmes, particularly for those who suffer from reshuffling of activities, such as fisheries. Multiple-use of space can be an enabler when it reduces human activities overall, but a barrier in case it leads to a rebound effect wherein more activities take place in the same space, aggravating already existing political tensions (R5, R6). Finally, the state of nature can be a barrier for offshore wind because of its own ecological impact or because other sectors such as shipping and fishing reduce the quality of nature, ultimately affecting the socially and ecologically acceptable level of offshore wind (B3, B7*, B9). However, quality of nature can be an enabler if eco-design can lead to a higher quality of nature (B8) or when other ecologically more harmful sectors are displaced by offshore wind (B10).

Table 2: Barriers and enablers of the offshore wind energy transition in the Dutch North Sea. The feedback loops relate to the ones in Figure 4, Figure 5, and Figure 6.

Barrier	Feedback loop & justification
Socio-political impact of extensive electricity and hydrogen infrastructure	B4, B5: acceptance limit for infrastructure close to residents' vicinity
State of nature	R7: negative effect on birds & bat populations B7*: bad state of nature limits offshore wind ambitions
Lack of space	R5, R6*: offshore wind aggravating spatial pressure despite multiple use
Political conflict due to the displacement of other sectors	R4: other sectors are getting displaced by the offshore wind infrastructure
Enabler	**Feedback loop & justification**
Energy demand	No feedback loop, but has an effect on profitability and desired offshore wind capacity (R1*)
Offshore energy hubs	B2*: offshore energy hubs can increase the profitability of far away offshore wind
Deliberate reduction of human activities	R5, R6*: reduction of human activities gives more space to offshore wind and makes multiple-use more effective in reducing spatial competition B11, B12: human impacts on nature are reduced, increasing the available carrying capacity for offshore wind
Include coastal communities in energy transition	B4, B5: acceptance of grid infrastructure depends on whether communities can benefit from them B11, B12: activities happening in the North Sea depend on communities' willingness to pursue them and live with their consequences
Both	**Feedback loop & justification**
Energy System Integration	R1*: lack of system integration reduces profitability ↔ system integration increases profitability R2*: lack of hydrogen infrastructure increases the need for electricity grids, causing resistance ↔ hydrogen infrastructure reduces the need for electricity grids and, hence, resistance
Profitability of offshore wind	R1*: lack of profitability reduces offshore wind deployment ↔ profitability increases offshore wind deployment B2*: profitability determines how far offshore wind farms can be deployed offshore
Port capacity & supply chain	B1*: port capacity determines offshore wind capacity B6*: port capacity determines the extent of other activities and thereby spatial competition, impacting offshore wind capacity
Local job creation	R3: local communities don't get jobs in the offshore wind industry ↔ local communities get jobs in the offshore wind industry
Multiple-use	R5, R6*: multiple use leading to more activities and, hence, more spatial competition ↔ multiple-use is complemented by reduction of overall activities
Environmental policies	B3: deployment of offshore wind is highly dependent on ambitions to reduce GHG emissions B8: quality of nature is dependent on environmental policies B9: offshore wind capacity is contingent on cumulative activities' impact on nature, dictated by environmental policies B10: Environmental policies guide offshore wind's impact on nature and, hence, its capacity

5 Discussion

The aim of this study is to identify barriers and enablers of the offshore wind energy transition in the Netherlands. Through our systems thinking approach and by building on participative modelling and methods, we manage to shed light on the complex landscape of interrelated interests in the Dutch offshore wind energy transition. We show that activities in the North Sea are connected via feedback loops and that interventions spread through different systems, affecting the deployment of offshore wind. We identify a set of mutually connected barriers and enablers, some of which fall under both categories (Figure 7). The barriers and enablers can be found in domains such as the techno-economics of (large scale) offshore wind deployment, spatial tensions, socio-political issues as well as ecology. In the following we will discuss the results in the context of our concepts, the already existing body of knowledge, and the methodology, followed by policy recommendations.

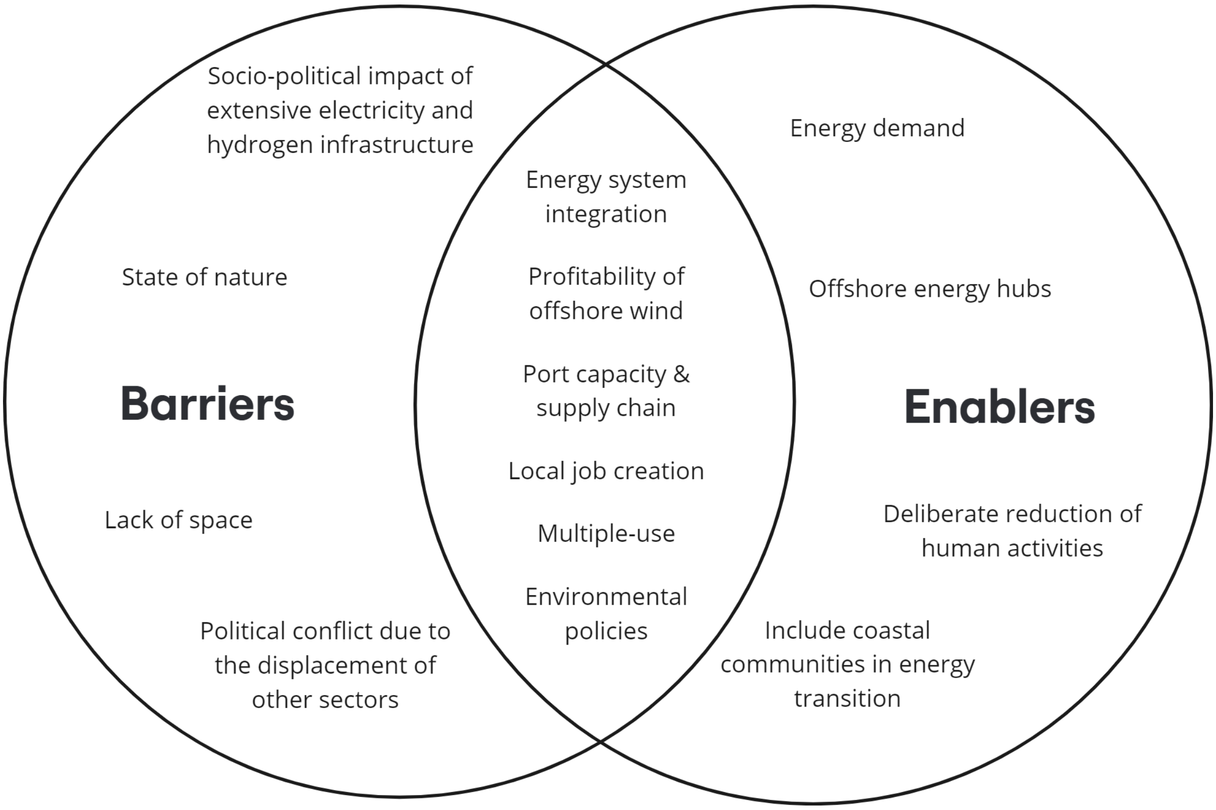

Figure 7: Barriers and enablers of the offshore wind energy transition in the Dutch North Sea. The overlapping area in the middle highlights that some factors can be both barriers and enablers. A description can be found in the text, barriers' and enablers' relation to the feedback loops can be found in Table 2.

Our systems thinking approach managed to shed light in the interconnected nature of different sectors, activities, and their impacts in the Dutch North Sea in the context of the offshore wind energy transition. Earlier work treats the different subsystems of the North Sea energy transition in isolation, for example by focusing on the techno-economics of (integrated) offshore wind (Jansen et al., 2022), environmental impacts (Leemans and Collier, 2022), and spatial considerations (Kusters et al., 2023). However, our approach is novel as it connects those different sub-systems for an integrated assessment. This multi-system interaction is the cause of many tensions, as they lead to various (unintended) consequences when singular interests are pursued. One manifestation of those tensions are political struggles and conflicts over access to material values such as space, confirming earlier work which underlines that transitions are intrinsically political (Meadowcroft, 2011; Normann, 2015). Because multiple barriers and enablers are present at the same time in different subsystems, there is clear need for holistic approaches to ensure the success of the transition, such as policy mixes, which can balance different interests and trade-offs (Rogge and Reichardt, 2016).

Offshore wind and its socio-political, ecological, and spatial implications are documented in literature, underlining that our identified barriers and enablers are in line with the existing body of knowledge. Regarding barriers such as the *socio-political impact of infrastructure*, Gonyo et al. (2021) show that offshore wind impacts communities which lead to resistance, potentially impeding the deployment. Leemans & Collier (2022) find that the impact of offshore wind on the *state of nature* is still ill-understood, warranting further studies which can help understand the extent of the impact of large scale offshore wind. Kusters et al. (2023) find that spatial competition complicates spatial planning for offshore wind, underlining that *lack of space* can act as a barrier to offshore wind. *Political conflict due to the displacement of other sectors* can impede offshore wind deployment, as shown by Smythe (2024).

Regarding factors which are both barriers and enablers, *energy system integration* leading to economies of scale which increase *profitability* is well-grounded in literature (Arthur, 1988). The *profitability of offshore wind* in integrated energy systems is still filled with uncertainties with studies pointing to opposing directions regarding its (financial) feasibility (Jansen et al., 2022; Koivisto et al., 2020; Wu et al., 2022). An assessment by Lammers et al. (2023) shows that *port capacity & supply chain* are currently bottlenecks for offshore wind deployment in the North Sea, however, they can act as enablers once their infrastructure and coordination will be matched to the ambitions. *Local job creation* is a factor which can enable acceptance by coastal communities, as shown by Gonyo et al. (2021). *Multiple-use* of sea areas can be accelerated by communities of practice, which bring parties together to experiment on ways to bringing activities and interests together in the same space through multi-use (Steins et al., 2021). *Environmental policies* impact the scale and speed at which offshore wind is deployed, as shown by Vasconcelos et al.'s (2022) comparative study on environmental licensing regimes.

In terms of enablers, Zhang et al. (2022) show that *offshore energy hubs* can be beneficial for the energy system integration of offshore wind, showing that they can enable large scale offshore wind deployment. *Including coastal communities in the energy transition* acting as an enabler is supported by Park et al. (2022), who show that a just transition and participatory planning by including fishing communities can be beneficial for offshore wind deployment. Salvador & Ribeiro (2023) too show that involving coastal communities in offshore decision-making processes can increase their social acceptance, for example in marine spatial planning (Griffiths et al., 2025). However, we haven’t found literature which identifies *energy demand* and the *deliberate reduction of human activities* as enablers of the offshore wind transition process.

We see those two factors as key contributions from our research, which stem from our systems thinking approach, and which would have likely been hidden in single system analyses. Energy demand as an enabler for offshore wind transitions refers to pairing the energy demand to the supply profile, which impacts the business case and profitability of offshore wind. This also means that energy demand as an enabler would require technological and behavioural adaptions on land, for example by enabling flexible energy demand in residential households and industry, and increasing hydrogen demand for industries, in case (offshore) hydrogen production will be realised. Deliberate reduction of human activities as an enabler stems from the scarce ecological carrying capacity and space in the North Sea. If other activities such as shipping, fishing, and so forth, would be reduced in the North Sea, the freed up physical and ecological space would ease the deployment of offshore wind.

Regarding the methodology, our approach allowed us to reveal various dynamics in the offshore wind transition in the Dutch North Sea. Causal loop diagrams have the ability to elucidate complex processes and structures. However, by employing such a view, other realities and dynamics are inherently concealed. For example, we assume the connection between two variables to be either positive or negative. In real systems, those relationships are more facetted, as for many connections there are certain thresholds before or after which it may disappear or change its type. This, in turn, also impacts feedback effects. Furthermore, the individual system variables can be broken down in complex systems themselves (Meadows, 2008). System structures are under constant change, potentially leading to different constellations after a certain period of time.

Another limitation of CLDs and GMB are framings and labels of different variables. Group Model Building exercises lead to consensus views among participants, but there is always a certain risk that participants have different interpretations of certain variables (Scott, 2018). The output is highly dependent on who is in the room, but having participants with different backgrounds can lead to more robust results (Scott, 2019). The dynamics between the different participants can have substantial impact on the CLD, for example because some participants may withhold information (Rouwette and Franco, 2024), which can be overcome by effective workshop delivery (Hovmand, 2014).

To summarise, since the offshore wind policy push will lead to various (un-)intended consequences in various domains, there is a clear need to broaden decarbonisation strategies by combining it with other policies, forming a policy mix (Rogge and Reichardt, 2016). Such an offshore wind policy mix should overcome the identified barriers and strengthen the enablers, ultimately increasing the likelihood of a socially and ecologically sustainable offshore wind transition. Central to this effort are inclusive governance processes and the appreciation of political processes. Given the bad state of nature and scarcity of space, efforts should be undertaken to limit all activities in the Dutch North Sea, while taking into account the needs and requirements of the Dutch society.

5.1 Policy Implications

We identify three promising strategies which can align different interests from the start into transition objectives, which can strengthen the mandate from the different users. All strategies bundle sets of actions which take into account the identified relationships and feedbacks, address the barriers and enablers, and contribute to an offshore wind energy transition in the Netherlands which is environmentally and socially sustainable. We call those strategies (i) collaborative governance; (ii) ecosystem based planning; and (iii) energy system transformation, which are explained in the following, and a summary can be found in Table 3.

Collaborative governance deals with collaboration between governments of the North Sea countries and between various societal stakeholders within the Netherlands. The North Sea Energy Cooperation can support the integration of offshore wind into the European energy system, for example by planning grid infrastructure and aligning offshore wind deployment to reduce the strain on the wind supply chain. The already existing Dutch platform ‘Noordzeeoverleg’ is a vehicle which can open the collaboration and enable bottom-up approaches supporting top-down decisions. The ‘Community of Practice Noordzee’ is another forum which can enable joint learning between different stakeholder groups, for example for multi-use strategies. The goal of these collaborations is to have an alignment of a shared vision leading to a certain policy stability amidst political changes. However, there should be sufficient flexibility within those policies to ensure that crises can be adequately responded to. Higher citizen engagement in offshore wind, for example by replicating the onshore energy community model offshore, can increase acceptance and the participation of (coastal) communities in the transition. Groups who may be negatively affected by the offshore wind transition, such as fisheries and coastal communities, shall be sufficiently supported by the government, for example via education programmes or financial resources to invest into sustainable technologies.

Ecosystem based planning is about centring all planning related activities around the functioning of the North Sea’s ecosystem. Marine spatial plans should be based on ‘nature inclusive design’, which contributes to the creation of habitats for marine life. Environmental impact assessments can be transformed into environmental outcome assessments, wherein the analysis centres around what is needed to reach a certain ecological outcome rather than to prevent a certain ecological impact. Multi-functional use should reduce activities’ cumulative spatial footprint instead of intensifying their spatial impact, hence they should be complemented with a reduction of overall activities. Nature should be given greater value in offshore wind tenders, for example through ecological passports for wind farms.

Energy system transformation entails a holistic energy system transformation strategy which takes into account the whole energy value chain. Electricity and hydrogen grids spanning over the whole North Sea connecting multiple countries, which are complemented by offshore energy hubs where you collect and distribute energy, could set in motion economies of scale. These hubs can simplify operations and maintenance activities and integrate offshore wind into the wider energy system, for example through hydrogen production. Upgrading onshore grids would enable flexible electricity demand, and creating hydrogen demand could create a business case for offshore hydrogen. The need for energy infrastructure can be reduced by lowering energy demand through efficiency and sufficiency measures. Technology wise, standardisation of turbine sizes can stop the race to the bottom of turbine technology and thereby reduce the pressure on ports. The focus should be innovations in turbine designs and operation, increased testing of new technologies, and stronger cooperation between companies along the supply chain. Offshore wind farms’ business case can be supported via power purchase agreements and contracts for difference, or by removing negative bidding.

Table 3: Strategies which can accelerate the offshore wind energy transition in the Netherlands. The barriers and enablers are the ones from Figure 7 and the letter in brackets indicates whether they are barriers (B), enablers (E), or both (B, E). The strategies are explained in the text.

Strategy	Collaborative Governance	Ecosystem Based Planning	Energy System Transformation
Barriers (B) and Enablers (E)	• Socio-political impact of electricity and hydrogen infrastructure (B) • Political conflict due to the displacement of other sectors (B) • Local job creation (B, E) • Include coastal communities in energy transition (E)	• State of nature (B) • Lack of space (B) • Multiple-use (B, E) • Environmental policies (B, E) • Deliberate reduction of human activities (E)	• Energy system integration (B, E) • Profitability of offshore wind (B, E) • Port capacity & supply chain (B, E) • Energy demand (E) • Offshore energy hub (E)
Actions	• International cooperation within NSEC • Foster dialogue between stakeholders in the North Sea • Align on shared North Sea vision between stakeholders • Citizen engagement in offshore wind • Support groups which are negatively affected by transition	• Nature inclusive design • Environmental outcome assessment • Set-up limits of human activities • Ecological passports for wind farms	• Energy Backbone • Promote onshore electricity & hydrogen demand • Reduce overall energy demand • Targeted innovation • Investment support schemes

6 Conclusion

This research used a participatory systems thinking approach to illuminate the feedback mechanisms in the Dutch offshore wind energy transition and to investigate which barriers and enablers affect the transition process. Our findings highlight that transition strategies should have a stronger focus on systemic perspectives and multi-system interactions from the start, particularly the interaction between offshore wind capacity, spatial competition, and the impact on nature. Since developments in one system can permeate into others, single system analyses focusing on themes such as business cases or technical optimisation need to be complemented by perspectives such as spatio-politics, socio-economics, and ecology. Understanding how the business case and the optimal size of offshore wind will be affected by this multi-system interaction would require further lines of inquiry. We want to emphasise that the Netherlands is already reaching its limits to growth both from an ecological and spatial perspective. Hence, the expansion of offshore wind will need to go hand in hand with changes in the current usage profile, ideally by downsizing human activities on sea and reducing energy demand on land through efficiency and sufficiency measures.

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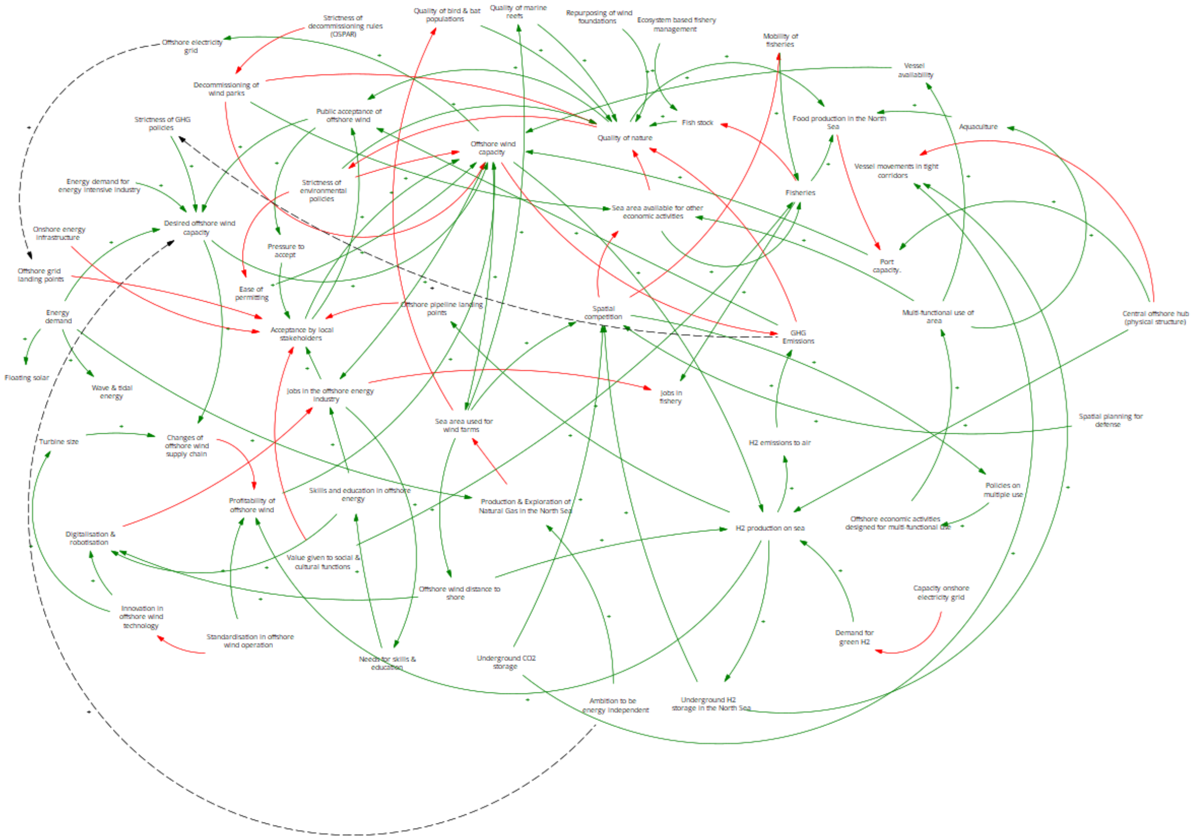
8 Annex

A - Interview Guide

Theme	Question	Rational / Expected information
Understanding of system dynamics in the North Sea	1.1. What is your understanding of an energy system? 1.2. To what extent are you familiar with the concept system dynamics?	1.1. People can elaborate on what they understand under systems 1.2. This can give me a feel of how familiar people are with the concept. This question may be redundant based on the response to the previous question.
Problem definition – status quo	2.1. What is your definition of the Dutch North Sea? 2.2. What are important variables which can help describe the North Sea? 2.3. Which are important sectors and actors of the North Sea? 2.4. What kind of impact do these sectors have on the North Sea? How? 2.5. Which problems does the North Sea currently face? 2.6. What is the role of the sectors in the problem? Why / how? 2.7. To what extent do you think shall use the North Sea? How much space shall be given to ecology, how much to economy? 2.8. Would you describe the current usage of the North Sea as sustainable or unsustainable? Why (not)?	2.1. Contextualise their understanding and statements 2.2. elicitation of system variables in relation to the North Sea 2.3. list of crucial sectors of North sea 2.4. elicitation of current feedback relationships 2.5. Problems which are relevant interviewees or their business, could already hint at feedback relations 2.6. could give a better understanding of sectors' role with regards to the problem, hint at feedback relations 2.7. could uncover conflicts / different visions 2.8. helps understand interviewees' view on North Sea's sustainability
Future vision	3.1. What is your vision of a sustainable North Sea? What is the role of the environment, economy, society? 3.2. How can this vision be achieved? 3.3. Which issues are there when trying to achieve this vision? 3.4. Which issues does the North Sea currently face when talking about energy transitions, e.g. expansion of offshore wind? 3.5. Why do these issues exist? 3.6. What is the role of the different sectors when tackling those issues? How can these sectors accelerate the deployment of offshore wind? 3.7. Which external influences impact the way the transition in the North Sea unfolds?	3.1. Elaboration on their vision which can help understand their framing regarding the decarbonisation 3.2. actions from sectors and actors, which could hint at feedback relations 3.3. issue elaboration based on interviewees' perception 3.4. particular elaboration on energy related issues 3.5. reasons, which can be used for feedback relations 3.6. sectoral elaboration, which can help construct feedback relation 3.7. identification of exogenous variables 3.8. particular elaboration on potential solutions from interviewee's side, could hint on leverage points 3.9. elaboration on solutions

	3.8. To what extent are the decarbonisation goals of the North Sea realistic? 3.9. How do you think the energy transition can be accelerated in the North Sea?	
Additional questions	4.1. Is there anything else which you want to share?	4.1. check-in if something hasn't been addressed which should be addressed. Interviewees can add additional perspectives, which may have not been addressed in the interview

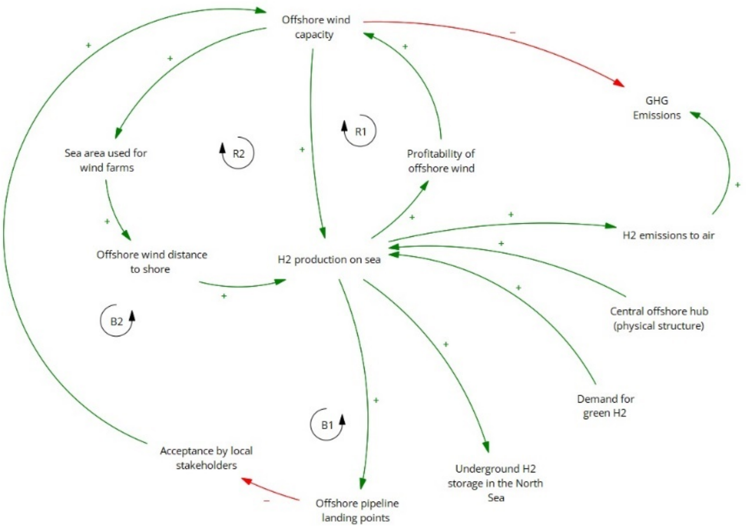
B - Main Causal Loop Diagram



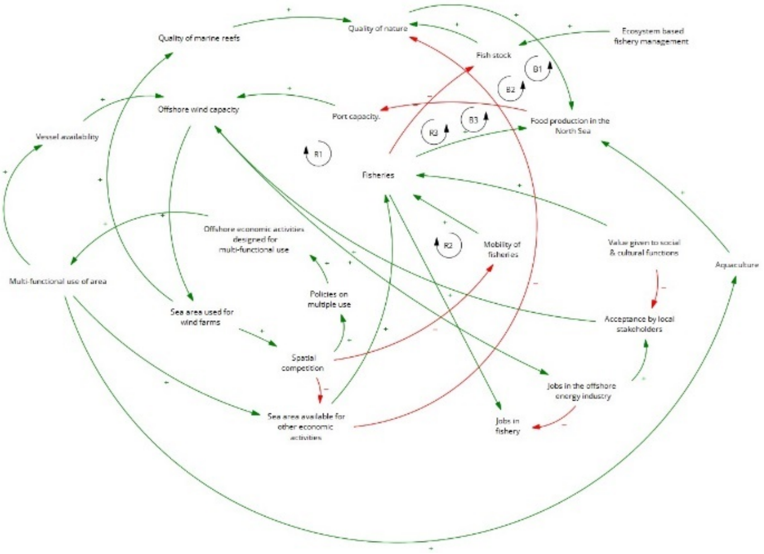
C -

Other Three Submodels

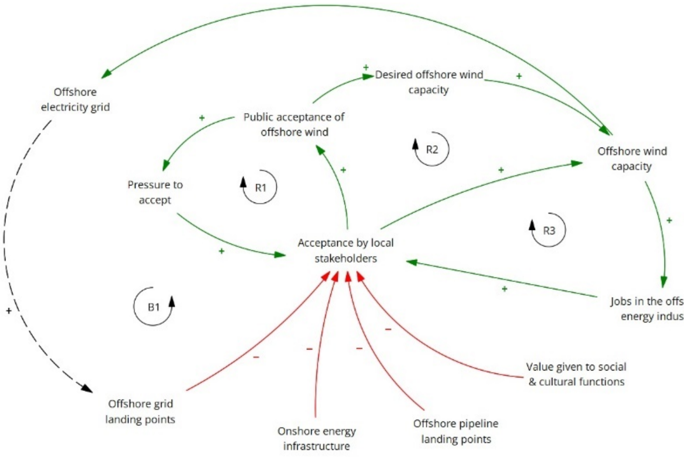
1) Hydrogen production on sea:



2) Fisheries



3) Acceptance by local stakeholders



D - Explanation of Feedback Loops

Feedback Loop	Description
	Offshore wind capacity
R1*	1: Offshore wind capacity → Need for energy storage → H2 production on sea → Profitability of offshore wind → Offshore wind capacity 2: Offshore wind capacity → Offshore wind distance to shore → H2 production on sea → Profitability of offshore wind → Offshore wind capacity 3: Offshore wind capacity → Need for energy storage → H2 production on sea → Profitability of offshore wind → Desired offshore wind capacity → Offshore wind capacity 4: Offshore wind capacity → Offshore wind distance to shore → H2 production on sea → Profitability of offshore wind → Desired offshore wind capacity → Offshore wind capacity
R2*	1: Offshore wind capacity → Need for energy storage → H2 production on sea → Offshore electricity grid → Onshore landing points → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity 2: Offshore wind capacity → Offshore wind distance to shore → H2 production on sea → Offshore electricity grid → Onshore landing points → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity
R3	Offshore wind capacity → Jobs in the offshore energy industry → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity
B1*	1: Offshore wind capacity → Port capacity → Vessel availability → Profitability of offshore wind → Offshore wind capacity 2: Offshore wind capacity → Port capacity → Vessel availability → Profitability of offshore wind → Desired offshore wind capacity → Offshore wind capacity
B2*	1: Offshore wind capacity → Offshore wind distance to shore → Profitability of offshore wind → Offshore wind capacity 2: Offshore wind capacity → Offshore wind distance to shore → Profitability of offshore wind → Desired offshore wind capacity → Offshore wind capacity
B3	Offshore wind capacity → GHG emissions → Strictness of GHG policies → Desired offshore wind capacity → Offshore wind capacity
B4	Offshore wind capacity → Offshore electricity grid → Offshore grid landing points → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity
B5*	1: Offshore wind capacity → Need for energy storage → H2 production on sea → Offshore pipeline landing points → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity 2: Offshore wind capacity → Offshore wind distance to shore → H2 production on sea → Offshore pipeline landing points → Acceptance by local stakeholders → Public acceptance of offshore wind → Desired offshore wind capacity → Offshore wind capacity
	Spatial Competition
R4	Spatial competition → Offshore wind distance to shore → H2 production on sea → H2 infrastructure → Spatial competition

R5	Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional use → Multi-functional use of area → Sea area available for other economic uses → Other economic uses → Spatial competition
R6*	1: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional use → Multi-functional use of area → Sea area used for wind farms → Spatial competition 2: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional use → Multi-functional use of area → Sea area used for wind farms → Offshore wind distance to shore → H2 production on sea → H2 infrastructure → Spatial competition
B6*	1: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional se → Multi-functional use of area → Sea area available for other economic uses → Other economic uses → Port Capacity → Offshore wind capacity → Sea area used for wind farms → Spatial competition 2: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional se → Multi-functional use of area → Sea area available for other economic uses → Other economic uses → Port Capacity → Offshore wind capacity → Sea area used for wind farms → Offshore wind distance to shore → H2 production on sea → H2 infrastructure → Spatial competition
B7*	1: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional se → Multi-functional use of area → Sea area available for other economic uses → Other economic uses → Quality of nature → Strictness of environmental policies → Offshore wind capacity → Sea area used for wind farms → Spatial competition 2: Spatial competition → Policies on multiple use → Offshore economic activities designed for multi-functional se → Multi-functional use of area → Sea area available for other economic uses → Other economic uses → Quality of nature → Strictness of environmental policies → Offshore wind capacity → Sea area used for wind farms → Offshore wind distance to shore → H2 production on sea → H2 infrastructure → Spatial competition
	Quality of nature
R7	Quality of nature → Strictness of environmental policies → Ease of permitting → Offshore wind capacity → Sea area used for wind farms → Quality of bird & bat populations → Biodiversity → Quality of nature
B8	Quality of nature → Strictness of environmental policies → Quality of nature
B9	Quality of nature → Strictness of environmental policies → Ease of permitting → Offshore wind capacity → GHG emissions → Quality of nature
B10	Quality of nature → Strictness of environmental policies → Ease of permitting → Offshore wind capacity → Sea area used for wind farms → Hard substrate → Marine reefs → Biodiversity → Quality of nature
B11	Quality of nature → Strictness of environmental policies → Ease of permitting → Offshore wind capacity → Sea area used for wind farms → Sea area available for other economic uses → Quality of nature
B12	Quality of nature → Strictness of environmental policies → Ease of permitting → Offshore wind capacity → Sea area used for wind farms → Sea area available for other economic uses → Fisheries → Fish stock → Biodiversity → Quality of nature

North
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Energy
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system
integration

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Shell Nederland
NAM
EBN
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ONE-Dyas
DEME Dredging
Neptune Energy Netherlands (after ENI)
HINT Global
Noordgastransport
NOGAT
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