Renewable Energy 275 (2026) 126286

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

System interactions constraining offshore wind deployment in the Dutch North Sea

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ABSTRACT

The Netherlands aims to deploy up to 70 GW of offshore wind by 2050 in its waters. As one of the busiest sea areas in the world, the Dutch part of the North Sea is shaped by 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 leads to various interactions with spatially demanding offshore wind, potentially enabling and constraining its deployment. We use systems thinking to explore the interactions which occur in the Dutch North Sea as a result of the offshore wind transition. We interview 22 stakeholders, organise one structured focus group discussion, and four follow-up workshops. Through our systems thinking approach, we elucidate on the interactions between different sectors and activities in the domains of the socio-technical system of offshore wind, spatial competition, and quality of nature, thereby broadening the scope of analysis. This allows us to identify a set of interactions which impact the deployment of offshore wind in the Netherlands, located in the domains infrastructure, society, space, and ecology. Overall, we find that the spatial and ecological interactions point to the need to build on synergies between different activities for a successful transition. As the expansion of offshore wind will lead to a variety of effects due to the interactions with other domains, there will likely be conflicts with other policy areas such as ecology and marine spatial planning.

1. Introduction

Renewable energy in the North Sea will play an important role in the European Union's (EU) ambition to reach net-zero greenhouse gas (GHG) emissions by 2050 [1]. In a memorandum of understanding with the United Kingdom, the North Seas Energy Cooperation pledged to deploy up to 300 GW of offshore wind capacity in the North Sea by 2050 [2], of which up to 70 GW shall be deployed in the Dutch exclusive economic zone [3,4]. Should these goals be realised, offshore wind capacity would increase by about a factor of 15 from 4.7 GW in 2024 [5] within 26 years. This may lead to significant spatial tensions, as 70 GW offshore wind would take up about a quarter of the Dutch North Sea [6].

The Dutch North Sea belongs to the busiest sea areas in the world. The Netherlands harbours vast fossil fuel infrastructure in its waters, such as oil & gas wells, pipelines, and industrial clusters around ports, resulting in a large spatial footprint for the existing energy infrastructure and trade [7]. Fishing contributes to North Sea countries' food supply and is part of the Dutch cultural heritage, making it an important stakeholder group. Another 'sector' which requires space is nature conservation. The EU Birds and Habitats Directives mandate EU member states to implement so-called Natura 2000 areas in their national legislation [8]. Around 20% of the Dutch North Sea is currently designated for nature protection [9], which shall increase to around 30% by 2030 due to the recently adopted EU Nature Restoration Law [10]. 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, and requires the full decommissioning of offshore installations at the end of their lifetime [11]. In a recent assessment, OSPAR concluded that the North Sea's habitats for marine life and seabirds are deteriorated due to issues induced by human activities, such as GHG emissions, noise, chemical pollution, and spatial tensions [12].

The expansion of offshore wind in the Netherlands is facing challenges, as a recent tender with zero bids exemplifies [13]. Combined with the spatial limitations, ecological requirements, and the interrelation of offshore wind with the other types of usage, the achievement of the Dutch offshore wind policy goals remains uncertain. Space, ecology, and other usages interact with offshore wind in various ways, potentially enabling and constraining further deployment. It is important to shed light on and respond to those interactions in the interest of the Dutch offshore wind transition.

We draw from systems thinking literature [14], arguing that understanding and responding to such a change in the use of the North Sea requires an approach which takes into account the different interactions

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https://doi.org/10.1016/j.renene.2026.126286
Received 22 April 2026; Received in revised form 11 August 2026; Accepted 11 August 2026
Available online 12 August 2026
0960-1481/

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 systems' structures [15]. Systems thinking is an approach which embraces relationships between different activities and transcends attempts which treat apparent problems in a simplistic cause-effect approach [16]. Particularly in contexts with great uncertainty pertaining to relevant variables and factors, such explorative qualitative system dynamics can prepare the ground for future (quantitative) studies.

In this research, we respond to the research question 'How is the deployment of offshore wind in the Netherlands affected by interactions with other domains?' using systems thinking. The stakeholders in the North Sea have different interests and mental models, which can be revealed by creating systems models through specialised workshops [17]. Such an approach is novel in the existing body of literature for offshore wind and marine spatial planning. It allows us to shed light on the interlinked dynamics between different sub-systems, providing more integrated insights which (side) effects can arise from large scale offshore wind deployment. The approach will be explained in the following section, alongside the methodology. In section 3 we present the models which help us identify interactions which occur in the offshore wind energy transition in the Netherlands. The results will be discussed in section 4, followed by conclusions in section 5.

2. Methodology

In this section, we 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.

2.1. Systems thinking as a method

A system consists of elements which are connected to each other, achieving a certain function or purpose [18]. Systems thinking is about appreciating those connections and seeing them as opportunities to modify a system's structure to achieve desired effects. 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 [16].

System dynamics is closely related to systems thinking and focuses on changes in systems over time, particularly due to a system's feedback loops (closed circles of causal relationships) and their temporal changes [19]. In applied and explorative research such as ours, system dynamics modelling can improve the understanding of problems, resulting in new and practically relevant knowledge [20]. Applied system dynamics is undertaken in contexts where participants come from various backgrounds [20]. Recent system dynamics scholarship has investigated energy transition challenges in the Dutch context, for example decarbonisation strategies of a chemical cluster [21], and effective climate policies [22]. In this article, we use system dynamics as our engagement framework to develop causal loop diagrams, which are constructed in group model building workshops.

2.1.1. 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 a negative relationship, the direction of change is opposite, so if A increases/decreases, B decreases/increases. 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.

Fig. 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 [21,22]. 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 [18]. 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 find feedback loops which are used to identify the interactions in the Dutch 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.

2.1.2. Group model building as an engagement tool

Group Model Building (GMB) is a method which can help tackle complex problems [23]. As highlighted by De Gooyert et al. [22], 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. A GMB workshop usually starts with divergent activities, followed by convergent tasks [24], while a facilitation team guides the participants through the process [25]. The outcome of such an exercise is a system model, in our research a causal loop diagram [26]. 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 [23]. Hovmand [17] argues that the key goal of GMB is to socially construct a boundary object [23], 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 [27]. GMB can build enduring agreement among research participants [26] because of persuasive content, structured arguments, and building trust, among other factors [28]. 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, 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 [29]. Our focus is to learn about the system with the research participants and to identify the interactions in the Dutch offshore wind transition by building on the insights from relevant stakeholders. In the following we will describe the research process which led to the development of CLDs and the identification of interactions. Interested readers are advised to go to Refs. [23,30,31] for a more detailed description of GMB and CLDs.

2.2. Research process

The research process is illustrated in Fig. 2. After identifying offshore

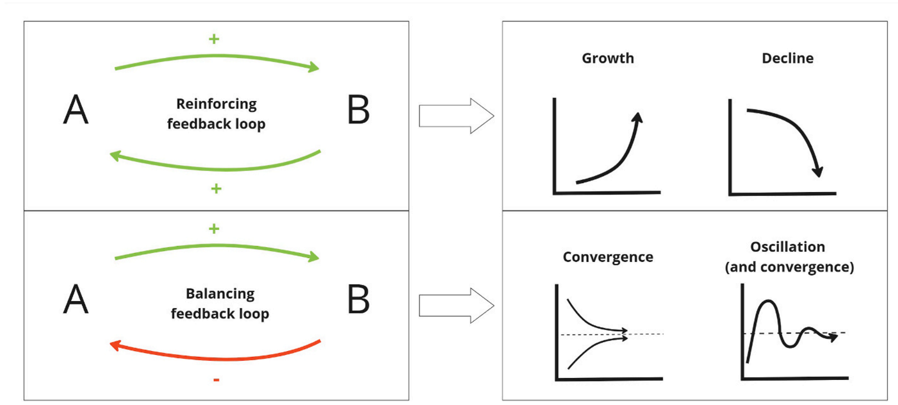

Fig. 1. Impact of reinforcing and balancing feedback loops on system parameters. Reinforcing feedback loops can lead to exponential growth and decline, whereas balancing feedback loops can cause system parameters to converge to a certain value and oscillate around/towards a certain value.

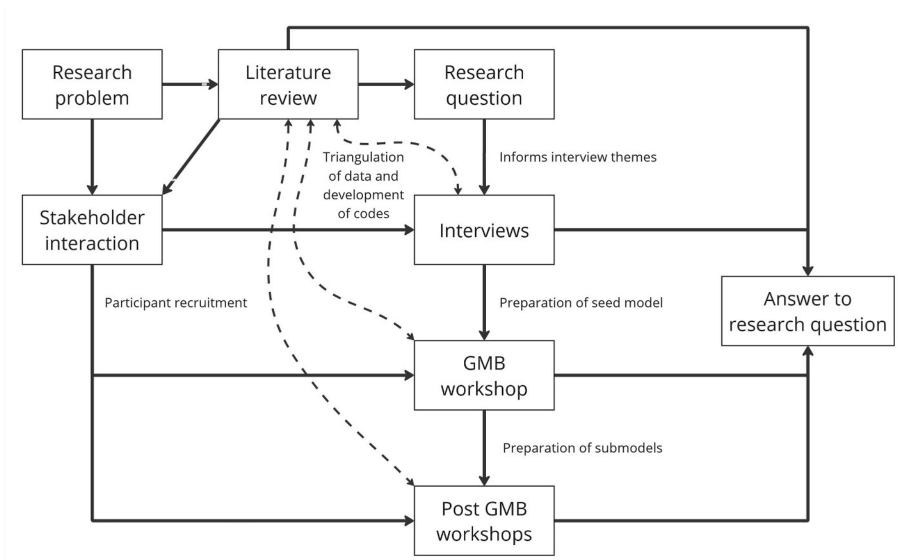

Fig. 2. Illustration of the research process, inspired by De Gooyert et al. [29]. The dashed lines stand for continuous processes to triangulate data and inform subsequent research steps with relevant literature.

wind expansion in the Dutch North Sea as the research problem, a literature review led to the formulation of the research question 'How is the deployment of offshore wind in the Netherlands affected by interactions with other domains?', which was accompanied by identifying and reaching out to relevant stakeholders. Throughout the research process, there was a constant iteration with the qualitative data collection through interviews and workshops, indicated by the dashed lines in Fig. 2. Our initial stakeholder mapping was derived from policies and grey literature, and interactions with participants of the North Sea Energy [32] 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 North Sea Energy 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 step can be found in Table 1.

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**

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 interview guide can be found in the supplementary material and the interviews were conducted in a semi-structured manner for around 45 min 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 [33] facilitated by the software NVivo [34]. 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, as with shipping companies.

Through the interviews and the coding, we gained an overview of the relevant issues in the Dutch North Sea regarding the deployment of 70 GW of offshore wind by 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, which was the starting point of the GMB workshop in September 2024 and was expanded during this workshop. This seed model can be found in Fig. 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.

The GMB was 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. The workshop lasted around 5 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 [35]. 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 sequence. Causal relations in this and subsequent steps were validated by triangulating between different data sources (literature, interviews, GMB) and experts correcting each other where necessary during the workshops. Furthermore, we cut the model into smaller sub-models 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 sub-models. We used those sub-models in the further research and they were sent to the participants for their comments. Three participants commented on the model results, however, they did not 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 subset of stakeholders. The rationale for bringing different stakeholder groups together rather than all sectors was to dive deeper into selected sub-models 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 interactions alongside barriers and enablers. We organised four workshops of 2.5 h with 3 – 5 participants each, their profile being shown in Table 1. An additional, shorter workshop was held during a review meeting of the North Sea Energy research programme. During those workshops, participants were invited to comment on the sub-models and modify the connections. Furthermore, we asked participants to share their perspectives on desired and undesired impacts of relevant sub-models on their sectors, list barriers and enablers to the offshore wind energy transition in the Netherlands, and suggest policy interventions. The post GMB workshops showed that themes kept reappearing during the discussion of the different sub-models, therefore not all sub-models were useful in elucidating new insights in the system's dynamics.

As a result, in the final step, instead of analysing all six sub-models, we focused on the three most relevant sub-models. We assessed their relevance based on the interview codes and participants' responses during the workshop. Furthermore, feedback relations of the three less relevant sub-models were nested in the most relevant sub-models, meaning that omitting the three models would not lead to a loss of information. The main sub-models which we identified are offshore wind capacity, spatial competition, and quality of nature. We identified feedback loops using Vensim [36]. We summarised feedback loops with similar causal mechanisms as one and highlighted them with a star symbol in the causal loop diagrams. Finally, the interactions were elucidated with the participants using the feedback loops in the models.

3. Results

In this section, we present the three sub-models in depth without a particular order. This is followed by a discussion of how the deployment of offshore wind in the Netherlands is affected by interactions with other domains. Reinforcing feedback loops are denoted with an R, whereas balancing feedback loops are denoted with a B.

3.1. Causal loop diagrams of the sub-models

In this section, we present the three sub-models which were developed in our research through the GMB and follow-up workshops (Fig. 2). These sub-models are about the (i) techno-economics and socio-politics of offshore wind capacity; (ii) change dynamics of spatial competition; and (iii) habitat changes affecting quality of nature. The explanations of

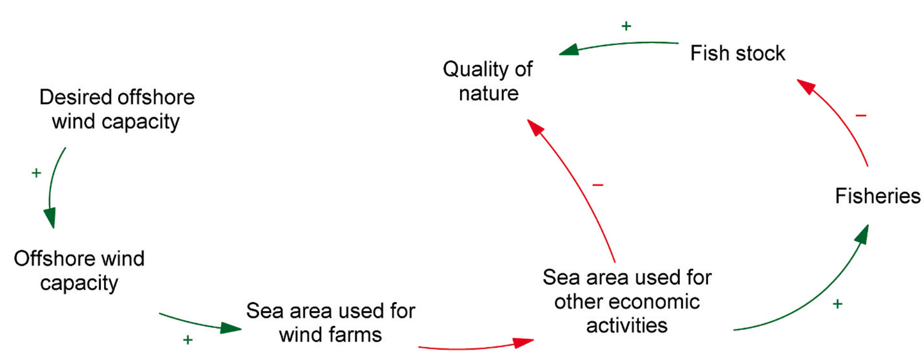

Fig. 3. Seed model which was developed for the GMB workshop and which is based on key themes in the preparatory interviews.

the feedback loops, the three other sub-models which were used during the follow-up workshops but omitted in the analysis, and the complete model can be found in the supplementary material.

3.1.1. Techno-economics and socio-politics of offshore wind capacity

The CLD for offshore wind capacity can be found in Fig. 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 interconnected. Below we dive deeper into each of the themes to provide a more detailed analysis of the dynamics.

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 create the need for higher energy (electricity) 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 the existing fossil infrastructure could be reused, 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 would not 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, offshore wind could not be profitable.

A key issue in the growth of offshore wind lies in its supply chain, for example port and vessel availability (B1*). Construction, operations and maintenance of offshore wind farms affect port infrastructure and increase maritime traffic. Offshore wind and potential hydrogen infrastructure will be visible in coastal areas, for example because of the landing points. This 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 lowering the extent of electricity grid infrastructure and thereby decrease 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 consequences on the fishing industry from offshore wind deployment can strongly affect local communities, because of job losses in the fisheries sector as well as a potential loss of socio-cultural value linked to the fishing industry.

3.1.2. Change dynamics of spatial competition

Fig. 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).

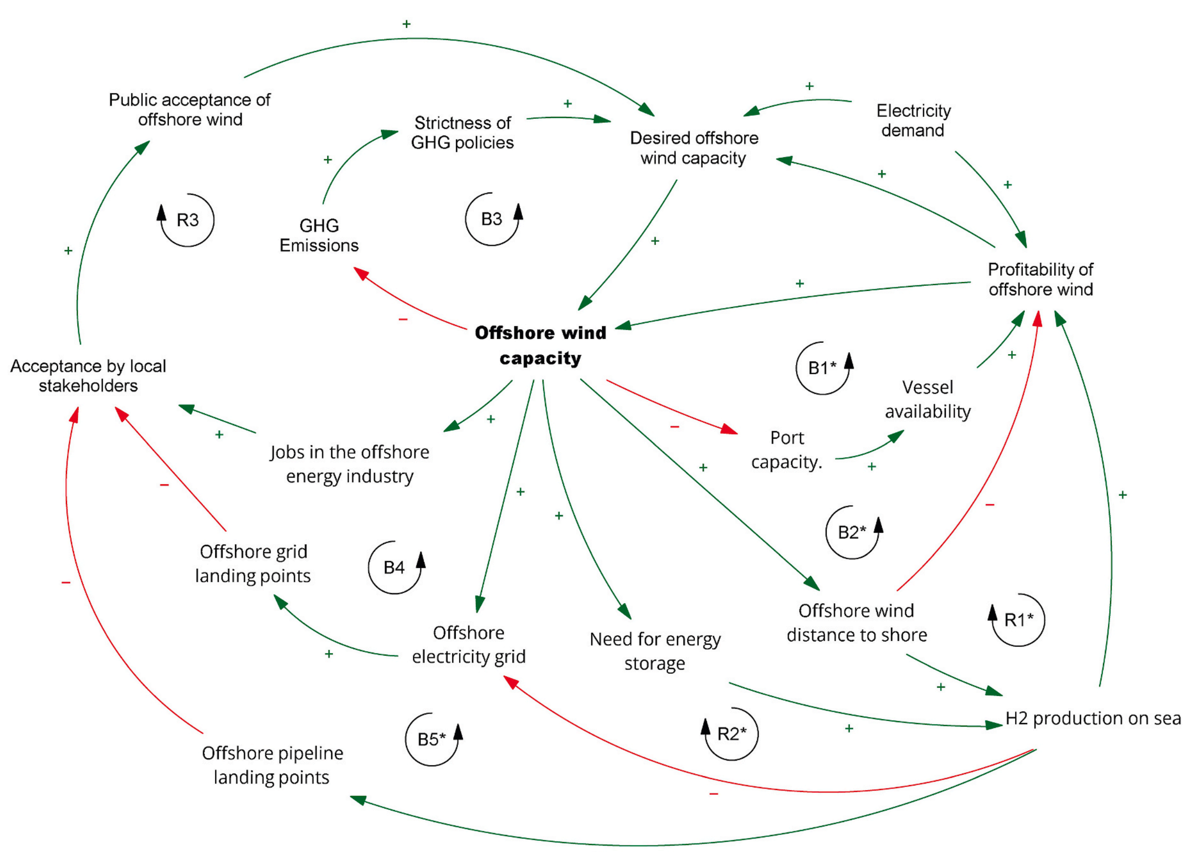

Fig. 4. CLD of offshore wind capacity. Feedback loops denoted with a star summarise two or more feedback loops taking a similar route, reflecting a similar causal mechanism. The descriptions for the different feedback loops can be found in the supplementary material.

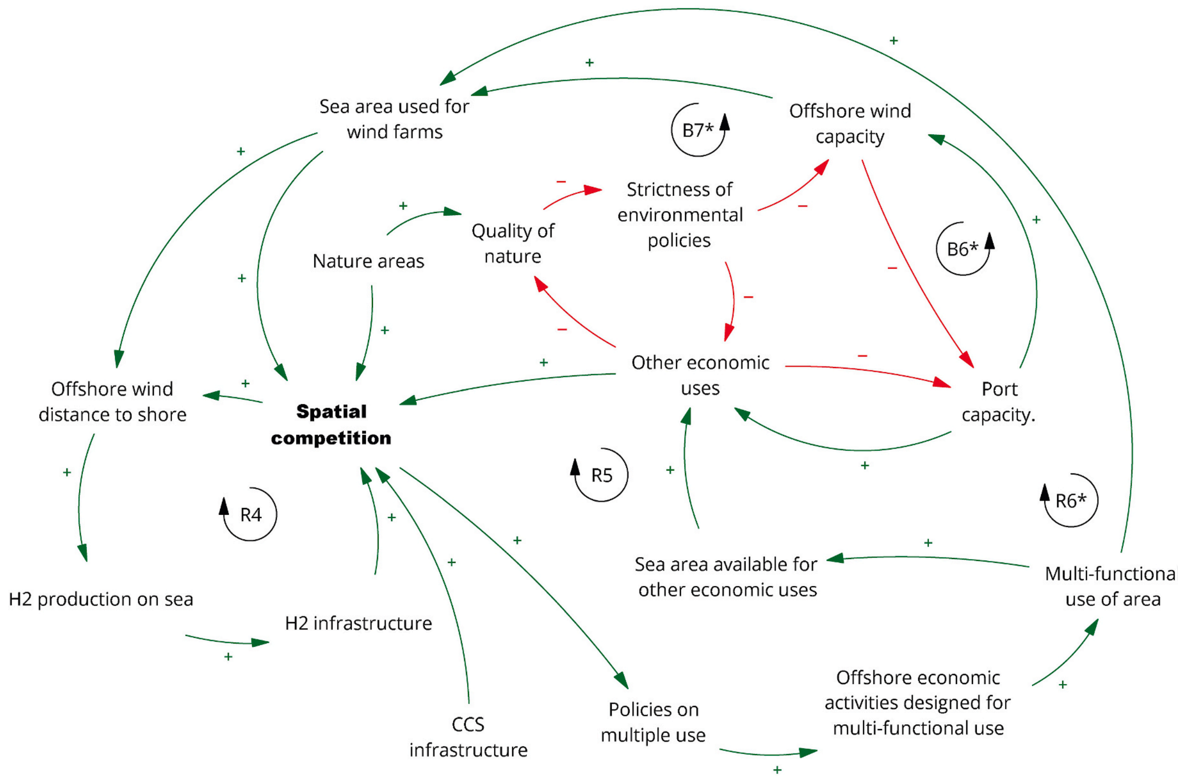

Fig. 5. CLD of spatial competition. Feedback loops denoted with a star summarise two or more feedback loops taking a similar route, reflecting the same causal mechanism. The descriptions for the different feedback loops can be found in the supplementary material.

Below we explore the dynamics in those themes.

Due to the scarcity of space, multi-use has been mentioned as a potential solution to use space more efficiently by pursuing multiple 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'. On a different note, 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 for 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 rearrangement 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 infrastructure would add to spatial competition.

3.1.3. *Habitat changes affecting quality of nature*

The CLD for quality of nature is shown in Fig. 6. Quality of nature, synonymous with 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 the role of environmental policies (R7, B8), changes in habitat (R8, B9), and the displacement of other human uses (R7, B8). These three themes are explained in greater detail below.

Quality of nature is highly dependent on environmental policies addressing habitats and pollution. They affect the impact human activities will have on nature, and their strictness depends on the quality of nature, making it converge to a level which is in line with policy ambitions (B8). Furthermore, offshore wind can reduce GHG emissions and thereby improve the quality of nature should environmental policies be sufficiently strictly designed (R7). Without adequately strict environmental policies, quality of nature gains through the mitigation of GHG emissions may be offset by the effects human activities will have on nature.

The impact of offshore wind on habitats is diverse. Offshore wind infrastructure may lead to higher levels of hard substrate and marine reefs, positively affecting quality of nature (R8). However, this only comes into effect a few years after installation of offshore wind turbines. 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 their associated infrastructure have to be decommissioned at the end of their lifetime, their positive effect would disappear. Another impact of offshore wind are detrimental effects on bird and bat populations (size and diversity), for example through avoidance, collisions, and barrier effects. However, this impact is contingent on the offshore wind capacity which will be deployed (B9).

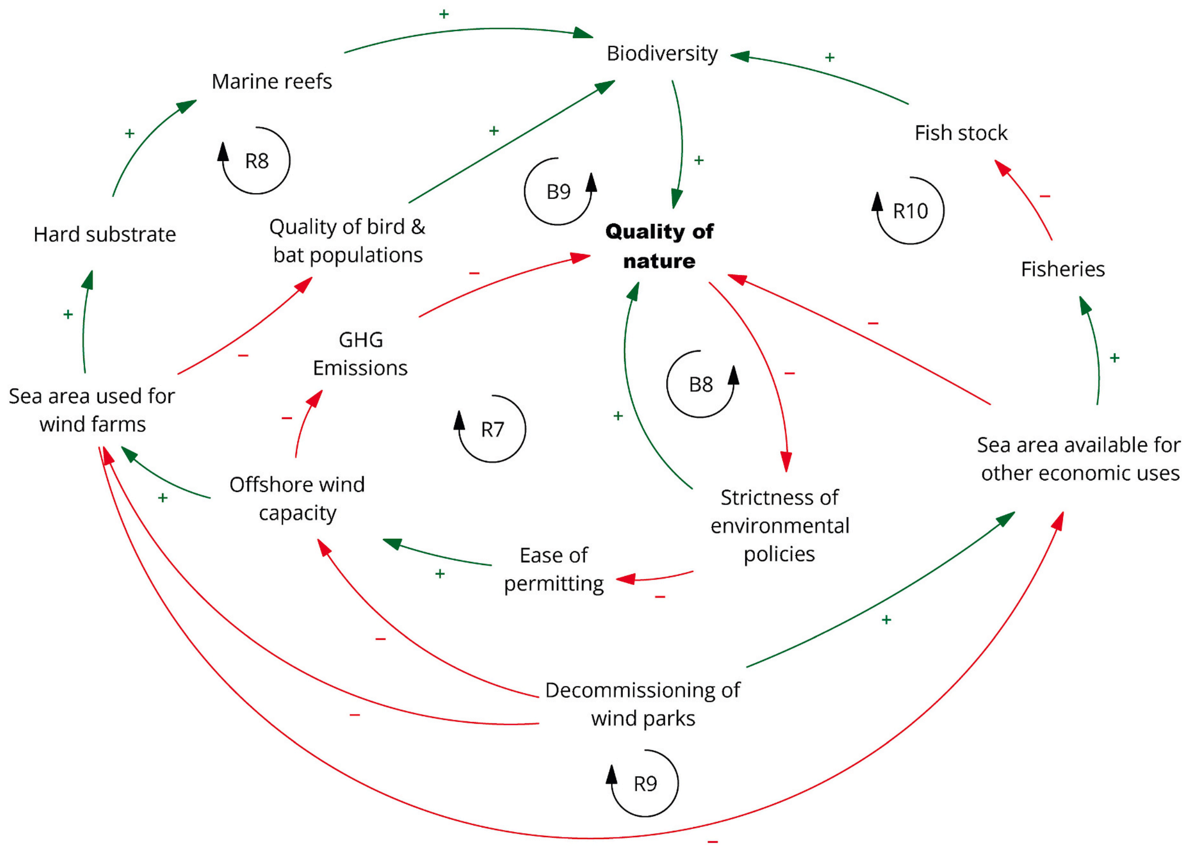

Fig. 6. CLD of quality of nature. The descriptions for the different feedback loops can be found in the supplementary material.

Another component affecting quality of nature is the displacement of other human activities. As all human activities tend to have negative effects on quality of nature in the North Sea, displacing those activities will have positive effects on marine life overall (R9). With fisheries causing detrimental effects on fish habitats, displacing those activities through offshore wind generates particularly high benefits for fish stock and, hence, the quality of nature (R10).

3.2. Interactions in the Dutch offshore wind transition

The three consensus models underline that various interactions occur due to the expansion of offshore wind in a context of limited space and ecological carrying capacity. Table 2 shows all feedback loops and we assigned different themes to them. From the perspective of infrastructure, the key interactions stemming from the large offshore wind goals include the expansion of energy infrastructure, a potential need to develop hydrogen as a storage and integration vector, the expansion of ports, and profitability considerations. In terms of infrastructure, offshore wind expansion is hence largely dependent on whether the supporting infrastructure can be developed in time. Ecologically, the deployment of offshore wind will significantly alter existing habitats. While short-term impacts may be severe, in the medium and long term marine life could profit, whereas bird and bat populations may decline. However, the already existing deteriorated state of nature, which warrants stricter environmental regulation, may inhibit large scale deployment of offshore wind in the short term due to said increased environmental requirements. This means that potential ecological gains in the long term may not be realisable due to the current bad state, putting the wider GHG emission goals at risk. In spatial terms, due to the already scarce available space and the ecological limits, the spatial tensions in the areas which can be used will likely increase and may offset any environmental gains which offshore wind could generate. By displacing or shifting existing usage types, offshore wind will likely lead to a number of conflicts, particularly with fishing communities. Access to space will remain a key consideration throughout the entire transition. Finally, from a societal perspective, the key interactions from large scale offshore wind deployment include acceptability considerations due to the expansion of grid infrastructure in coastal areas, and the impact on jobs due to the changing usage profile. It is, hence, important to centre acceptability concerns when deploying offshore wind infrastructure.

Our findings point towards the need to take these different interactions into account from the start. The large offshore wind ambition of 70 GW by 2050 may lead to various unintended consequences in ecological and spatial terms, which may inhibit the achievement of offshore wind goals in the long run. By building on synergies, such as multi-use of space and potential long-term improvements for the seabed, some negative effects can be mitigated. However, as the former may lead to increased maritime traffic and, thus, higher marine pressure, and the latter is contingent on the offshore infrastructure being in place, it remains questionable to what extent these synergies can deliver the intended benefits. By lowering the offshore wind ambition, spatial and ecological pressures connected to offshore wind infrastructure may be reduced. However, this may mean that hydrogen as a system integration vector may not be required, which would warrant other strategies to decarbonise the Dutch mainland. There are, hence, multiple options present which can impact the dynamics of the system. However, due to the system structure, the different options can lead to various consequences affecting the energy transition and ecological goals.

4. Discussion

The aim of this study is to identify how the deployment of offshore wind in the Netherlands is affected by interactions with other domains.

Table 2
Interactions of the offshore wind transitions. R stands for reinforcing, B for balancing feedback loop.

Feedback Loop	Interaction	Theme
R1*	Large scale offshore wind requires system integration through hydrogen or other means.	Infrastructure
R2*	Hydrogen replaces prospective electric grids and through that improves acceptance.	Society
R3	Job creation in offshore wind industry positively affects acceptance.	Society
R4	System integration leads to a large spatial footprint.	Space, Infrastructure
R5	Multi-functional use increases overall activities.	Space
R6*	Multi-functional use increases offshore wind activities.	Space
R7	Quality of nature profits from reduced GHG emissions due to offshore wind.	Ecology
R8	Offshore wind creates marine habitats.	Ecology
R9	Offshore wind displaces other uses, which improves quality of nature	Ecology, Space
R10	Offshore wind displaces fisheries, which improves fish stock.	Ecology, Space
B1*	Offshore wind capacity is contingent on port capacity.	Infrastructure
B2*	Profitability determines how far offshore wind can be deployed offshore.	Space, Infrastructure
B3	Offshore wind goals are determined by GHG emission reduction goals.	Ecology, Infrastructure
B4	Public acceptance is influenced by the extent of infrastructure (offshore wind grids).	Society, Infrastructure
B5*	Public acceptance is influenced by the extent of infrastructure (offshore hydrogen pipelines).	Society, Infrastructure
B6*	Offshore wind and other activities compete for port capacity.	Infrastructure
B7*	State of nature determines offshore wind ambitions.	Ecology
B8	Quality of nature depends on environmental policies.	Ecology
B9	Bird and bat population adjusts to offshore wind capacity.	Ecology

Through our systems thinking approach and by building on participative modelling and methods, we shed light on the complex landscape of interrelated dynamics in the Dutch offshore wind energy transition. Stakeholder perceptions show that activities in the North Sea are connected via feedback loops and that interventions spread through different systems. The interactions occur in the domains of infrastructure, space, society, and ecology, highlighting the multi-dimensional nature of the offshore wind transition. In the following we discuss the results in the context of the already existing body of knowledge and our concepts, followed by the limitations.

Our work relates strongly to earlier studies in this domain which research the integrated impacts of offshore wind [37,38]. In terms of infrastructure, energy system integration which leads to economies of scale is well grounded in literature [39]. However, with the profitability of offshore hydrogen [40] and integrated offshore wind systems [41,42] still being contested, it is yet to be seen whether these gains can be realised. We confirm an assessment by Haskoning Nederland BV that port capacity could be a limiting factor for offshore wind development [43]. From a societal point of view, we confirm earlier research showing that (offsetting) job losses in the offshore wind transition [44] as well as landscape effects of its infrastructure [45] will be key determining factors in the social acceptability of the offshore wind transition. Furthermore, political conflict due to the displacement of other sectors negatively interacting with the offshore wind transition is also shown by Smythe [46]. In ecological terms, environmental policies impacting the scale and speed at which offshore wind has been shown in earlier research [47]. Finally, from a spatial perspective, we confirm Kusters et al. [48] that spatial competition complicates offshore wind deployment. Our research, hence, replicates findings from earlier studies.

The key novelty of our study is the interactions which we identify and their interrelations. We find that the deployment of offshore wind may lead to a variety of effects, which may inhibit the achievement of the 70 GW offshore wind goal. These results are a direct outcome of our participatory systems thinking approach, through which we managed to shed light on the interconnected nature of different sectors, activities, and their impacts on the Dutch offshore wind transition. Earlier work treats the different sub-systems of the North Sea energy transition in isolation, for example by focusing on the techno-economics of (integrated) offshore wind [41], spatial considerations [48], and environmental impacts [49]. The novelty of our article lies in centring our focus on the connections between the different sub-systems. This allows us to shed light on the different interactions and the effects they can lead to, ultimately providing a more complete view of the change dynamics. Because multiple interactions are present at the same time in and between different sub-systems, there is a need for holistic approaches which build on synergies in the transition. However, as the ability to respond to multi-dimensional challenges through approaches such as policy mixes is disputed [50], there are significant uncertainties attached to the pathway forward.

4.1. Limitations

We identify a number of limitations which impact our study. First, while causal loop diagrams have the ability to elucidate complex processes and structures, they also conceal other realities and dynamics. For example, we assume the connection between two variables to be either positive or negative. In real systems, those relationships are more nuanced, as for many connections there are certain thresholds before or after which the connection may disappear or change its type. Second, qualitative CLDs contain limited information about the (relative) strength of feedback relations, interactions, and feedback loops. This can skew the results, as effects of different gravity may be treated with equal importance. Third, system structures are highly case specific and under constant flux. This reduces the generalisability of our results to other sea basins and, potentially, different system constellations after a certain period of time. Fourth, while GMB workshops tease out participants' consensus view of a certain context, there is always a certain risk that participants' interpretation of variables varies [26] and that participants purposefully withhold information [30]. Furthermore, the output is highly dependent on who is in the room, meaning that a different set of research participants can alter our results. However, particularly for this limitation, engaging with participants with diverse backgrounds [28] and effective workshop delivery [17] can mitigate those effects.

4.2. Future research

Our limitations present opportunities for future research. Our qualitative, explorative study could be complemented by quantitative approaches, which either model the same system or smaller sub-systems. This could (in)validate some of our findings. Furthermore, we would advise conducting similar research in other sea basins in the North Sea to test to what extent our results are confined to the Netherlands or also applicable to other areas. Finally, as every system can be broken down into smaller sub-systems, we believe that our coarse explorative analysis would profit from more fine-grained follow-up studies in distinct areas or regarding specific interactions.

5. Conclusion

This research used a participatory systems thinking approach to investigate the interactions in the Dutch offshore wind transition. Given how research participants see the system, we find a number of interactions in the domains of infrastructure, space, ecology, and society, all of which determine the extent to which the offshore wind goals can be realised. We also find a number of tensions, which seem to be caused by the size of the offshore wind ambition and the already existing dense activity profile. While some of the envisaged energy infrastructure is intended to contribute to the decarbonisation of North-Western Europe, our results suggest that the Netherlands may be reaching its ecological and spatial limits to growth in the North Sea.

With decarbonisation goals getting closer and the world crossing more planetary boundaries, there is an urgent need to act rapidly and effectively. Our research points towards some options for the way forward for the Dutch offshore wind transition and what effects certain pathways may stimulate. Should the Netherlands aspire to serve as the North-West European energy hub through large scale offshore wind, spatial contestation and ecological degradation will likely increase. This increase stems from the infrastructural requirements of offshore wind, the already dense activity profile, and the ecological effects of those activities. While mitigation measures such as multi-use of space may reduce some of the spatial effects, potential rebound effects through the increased maritime traffic may dampen the benefits. Should the Netherlands aspire to reduce the offshore wind goals, the pressures on space and ecology would be lessened. However, this may put the Dutch hydrogen strategies at risk and warrant complementary measures. These complementary measures would need to reduce the already existing ecological impact of fishing and shipping and target the large energy demand on land. In any case, political decisions need to be made swiftly as to which strategy to pursue. Trying to bridge both pathways wherein offshore wind goals, spatial usage, and ecological benefits are equally maximised is highly uncertain due to the system interactions which we identify in the causal loop diagrams. In the worst case, they may lead to severe negative consequences for the socio-ecological functioning of the sea basin.

CRediT authorship contribution statement

Ivo Wakounig: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Vincent de Gooyert:** Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2026.126286.

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