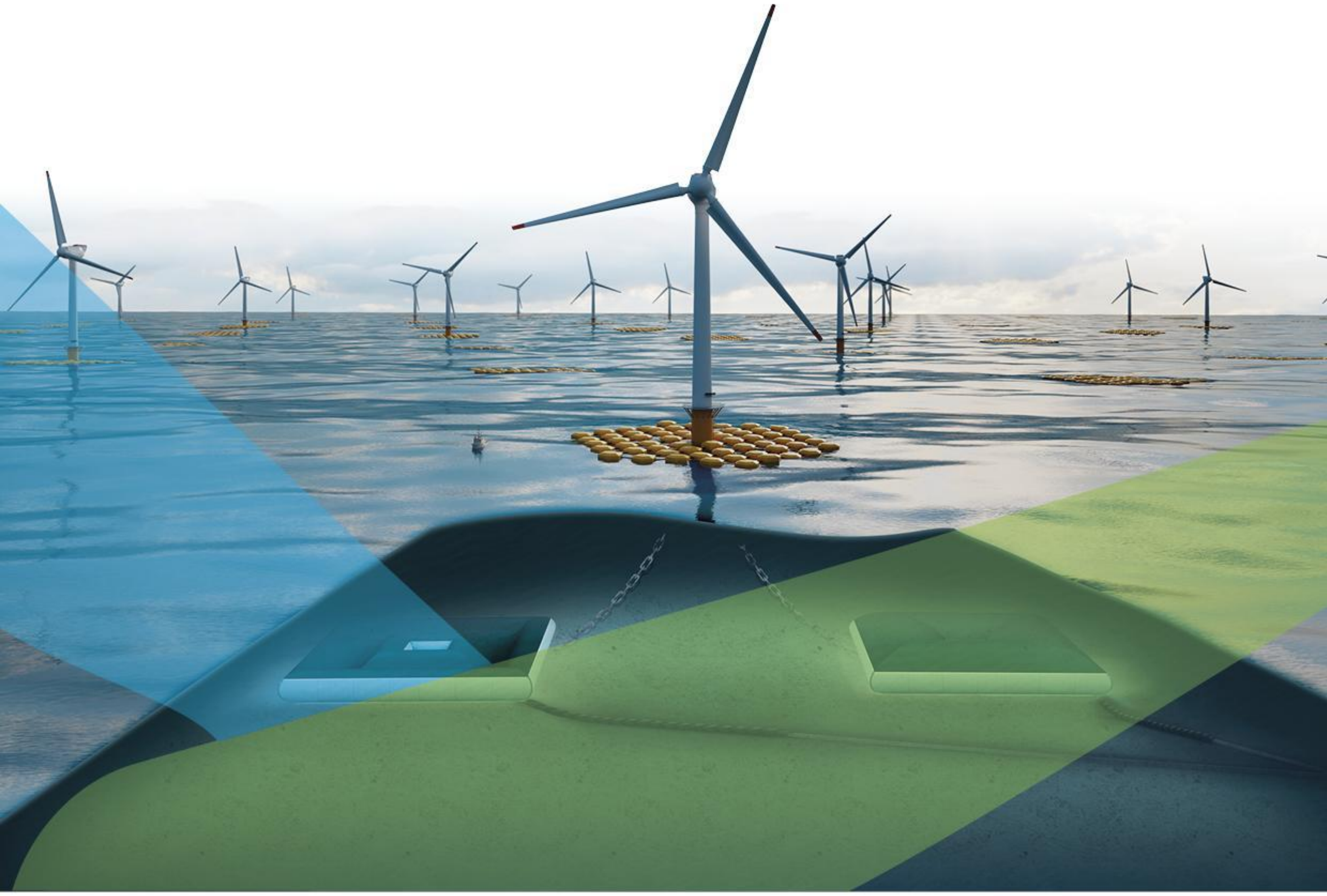
DOSTA | DEVELOPING OFFSHORE STORAGE AND TRANSPORT ALTERNATIVES



Developing Offshore Storage and Transport Alternatives

Findings from four years of interdisciplinary research

university of groningen

Utrecht University

Project name	DOSTA: Facilitating Large Scale Offshore Wind Energy Production by Developing Offshore Storage and Transport Alternatives
Duration	1 September 2020 – 1 September 2024
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Executive Summary

The DOSTA project (Development of Offshore Storage and Transport Alternatives) addresses the integration of innovative offshore energy technologies in the Dutch North Sea, focusing on their feasibility from technical, legal, and governance perspectives. The project aimed to support the Netherlands' ambitious offshore wind energy targets – 21 GW by 2030 and up to 72 GW by 2050 – by exploring solutions to challenges such as grid instability, rising cable costs, legal uncertainties, and nearshore spatial constraints. The project studied alternative offshore cable connections, energy storage systems, and offshore hydrogen applications.

- **Alternative offshore cable connections**: Current offshore cables are designed for one-way transmission from wind farms to shore. The project proposes the development of alternative cables that would connect multiple offshore wind farms to various national grids, as well as to offshore storage and conversion facilities, forming a meshed grid. This could reduce energy curtailment, stabilize prices, and enhance cross-border electricity exchange. However, planning such grids requires international cooperation and specialized regulatory frameworks, as current rules are predominantly national.
- **Offshore energy storage systems** (ESS): ESS, such as offshore batteries, compressed air storage, synthetic natural gas, hydrogen storage, and pumped-hydro storage, are critical for balancing supply and demand and minimizing onshore grid congestion. Of all available storage options, this project focused on the Ocean Battery, a novel offshore pumped-hydro energy storage technology. This concept can be deployed within or near an offshore wind farm and, as such, is a promising solution to store electricity when prices or grid capacity are too low.
- **Offshore power-to-hydrogen applications**: Hydrogen plays a key role as both an energy carrier and storage medium. Converting electricity to hydrogen already offshore could potentially diminish the need for lengthy and costly electricity cables. The project evaluated several scenarios for offshore hydrogen production, including the use of existing oil and gas platforms and pipelines. Producing green hydrogen offshore using wind energy is a promising way to reduce carbon emissions and extend the lifetime of existing infrastructure. However, economic feasibility remains a challenge, particularly for offshore hydrogen production compared to onshore options.

To provide a multi-faceted and realistic picture of the offshore energy system, the feasibility of deploying these technologies was explored from economic, technical, legal and governance perspectives.

Economic perspective – Modelling the offshore energy system

A comprehensive energy system model of the North Sea energy system was developed, analyzing the integration of these technologies by 2030. Results indicated that expanding the offshore electricity grid offers significant cost and emissions reductions, with grid expansion reducing emissions by up to 30%. Onshore and offshore energy storage could reduce emissions by up to 35.9%, but at a prohibitive cost. The study concludes that investing in offshore grid expansion is a "no-regret" strategy that delivers both cost savings and emission reductions.

Technical perspective – Assessing the technical feasibility of offshore energy storage

A technical case study of the Ocean Battery highlights that offshore energy storage can be deployed which operates within the same efficiency performance range as conventional pumped-hydro storage systems. While this shows promise, important questions such as the operational stability under combined loading of wind, wave, and external currents together with the impact of biofouling on the long-term durability of the system must be addressed before full-scale deployment. Offshore storage technologies, though essential, are expensive compared to onshore alternatives and require further development to optimize their efficiency and reduce costs.

Legal perspective – Legal design for new offshore storage and transport infrastructure

The project identified several legal and regulatory barriers to the deployment of these technologies. Existing legal frameworks are not adequate to support the offshore development of alternative cable connections, electricity storage, and hydrogen production and transport infrastructure. Legal gaps, regulatory uncertainty, and conflicting rules hinder investment and progress. Developing a comprehensive legal framework for offshore energy activities is essential to overcome these challenges and encourage private sector investment. For alternative offshore cable connections, the lack of a legal structure for multi-purpose offshore interconnectors hinders their development, and the lack of classification for other alternative offshore cables limits the ability to connect offshore storage and conversion facilities to offshore wind farms or the offshore electricity grid. Furthermore, offshore electricity storage, particularly when co-located with offshore wind farms, faces uncertainties in the planning and permitting process, while offshore hydrogen production requires clarification on the reuse of offshore natural gas installations and pipelines for hydrogen production and transport.

Governance perspective – Marine spatial planning, environmental impact, and spatial conflicts

The Dutch Program North Sea 2022-2027 outlines spatial use for offshore activities, but marine spatial planning processes often prioritize near-term goals, such as offshore wind development by 2030. Long-term planning for innovative energy technologies is limited. The project recommends incorporating hydrogen, energy storage, and alternative cable connections into marine spatial plans, allowing for more integrated planning and reducing spatial conflicts with other marine activities like fishing and shipping. Currently, spatial conflicts are resolved at the project level, rather than through a strategic, holistic view of the North Sea's usage.

Policy recommendations

1. *Embed alternative cable connections, offshore energy storage and power-to-hydrogen applications in the forthcoming North Sea Energy Infrastructure Plan*

The DOSTA project emphasizes the need for providing additional clarity on the role of alternative cable connections and offshore energy storage in the forthcoming North Sea Energy Infrastructure Plan. It recommends that the plan include provisions for multi-purpose interconnectors, regulatory clarity on generator-to-consumer and grid-to-user cables, streamlined permitting for co-locating energy storage facilities, and safety guidelines for new offshore activities.

2. *Invest in an expansion of the offshore electricity grid, notably cross-border connections*

Expanding the offshore electricity grid, particularly with cross-border connections (e.g., between Norway and other North Sea countries), is highlighted as a no-regret strategy. This expansion could reduce system costs by leveraging Norway's hydro resources, and potentially reduce the need for energy storage and hydrogen production. However, legal barriers at the EU level need to be addressed to facilitate the development of offshore generator-to-user and grid-to-user cables. Establishing specific rules for these new cable types and ensuring international coordination are crucial for optimizing the economic and environmental benefits of a more interconnected offshore electricity grid.

3. *Adapt EU and national energy laws to include provisions for emerging technologies and ensure their applicability within the Exclusive Economic Zone*

Current legislation does not adequately cover innovative offshore technologies like alternative cable connections, offshore energy storage, or hydrogen production systems. The recommendation is to ensure that the forthcoming Energy Bill includes these technologies within its scope and applies them to the Exclusive Economic Zone (EEZ).

4. *Strengthen cross-sectoral coordination in marine spatial plans and regulatory frameworks*

The existing Dutch planning processes and regulatory framework is largely sector-oriented, limiting its ability to adapt to innovative technologies and integrate different marine activities. The recommendation is to strengthen cross-sectoral coordination to balance offshore wind energy with other marine uses. Suggestions include explicitly incorporating novel technologies into updated marine spatial plans, providing clearer guidelines for integrating different energy elements in tenders and permits, and adopting a more integrated approach to the regulation of offshore activities to reduce legal uncertainty.

5. *Strengthen the role of environmental considerations in marine spatial planning processes*

The environmental status of the marine environment plays a critical role in decision-making regarding new offshore infrastructure. The recommendation is to give greater importance to environmental considerations in policymaking by initiating Strategic Environmental Assessments early in plan formulation processes. Strengthening the science-policy interface is also suggested to enable better collaboration among scientists, policymakers, and industry stakeholders, thus ensuring that ecological data inform strategic decisions for offshore energy developments.

6. *Facilitate and intensify transboundary collaboration to enable cross-border offshore energy developments.*

Offshore energy technologies, especially those involving cross-border cables, require more structured transboundary cooperation among North Sea countries. Harmonizing offshore wind and network regulations across borders could streamline planning and authorization, reduce costs, and facilitate cross-border hydrogen initiatives. Furthermore, the forthcoming Greater North Sea Basin Initiative offers a promising framework for structured collaboration. The recommendation is to focus on aligning national conflict resolution strategies, knowledge sharing, and collaborative spatial planning to support cross-border energy projects.

7. *Continue to stimulate interdisciplinary research to facilitate the development of an integrated offshore energy system.*

The DOSTA project highlights the importance of interdisciplinary research in understanding the technical, economic, legal, and governance aspects of offshore energy systems. It recommends that future research funding prioritize interdisciplinary approaches to address the existing knowledge gaps and uncertainties.

To conclude, the DOSTA project underscores the importance of integrating innovative offshore energy technologies into the Dutch North Sea energy system. The project’s findings highlight the potential for cost and emissions reductions, but also reveal significant hurdles in the technical development, regulatory frameworks and governance processes. A coordinated approach is essential to achieve the Netherlands' renewable energy goals, and immediate action is required to ensure the long-term success of offshore energy innovations beyond 2030.

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1| Introduction

To address climate change and energy security concerns, the Dutch government is aiming for 21 gigawatts (GW) of installed wind energy capacity in the North Sea by 2030. Scenarios for 2050 even range to a maximum of 72 GW, compared to an installed capacity of ~4,7 GW by April 2024. This planned upscaling of offshore wind energy poses several challenges. For one, this large-scale deployment of offshore renewables will have to be accommodated within an already intensively used offshore area. Given the scarcity of space close to shore, solutions will have to be sought farther offshore. Secondly, the increasing share of renewables raises several techno-economic concerns, including grid instability and grid flexibility constraints, intermittent energy supply and variable demand, and increased demand for costly sea-to-shore cables. In response, the upscaling of offshore wind requires a longer-term and strategic perspective upon an integrated offshore energy system. A central consideration for the development of such a perspective is the role of alternative forms of transporting and storing energy. The DOSTA project targets exactly this consideration, by investigating the development of alternative cable connections[1], offshore energy storage and power-to-hydrogen applications from an interdisciplinary perspective (see Box 1). This report summarizes the findings of four years of research in the DOSTA project.

About the project

The DOSTA project (Development of Offshore Storage and Transport Alternatives) addresses the feasibility of deploying innovative offshore energy technologies in the Dutch North Sea. Four PhD researchers from the University of Groningen and Utrecht University have explored this topic from economic, technical, governance and legal perspectives. The researchers also joined forces targeting interdisciplinary insights and explicit policy recommendations for industry practitioners and civil servants on the feasibility of the offshore storage and transport options analyzed in this project.

The project was supported by various industrial partners active in the offshore energy sector: Energie Beheer Nederland, ElementNL, Loyens & Loeff, NAM, NeVER, New Energy Coalition, NGT, NOGAT, Ocean Grazer, Siemens Energy, Smartport, TenneT, TNO, and Vattenfall.

The innovative offshore energy technologies studied within the DOSTA project support the development of a more integrated offshore energy system. Alternative offshore cable connections extend the traditional role of offshore cables, which currently transport electricity in one direction from offshore wind farms to shore. In the future, multi-purpose interconnectors may connect multiple offshore wind farms to different national transmission

[1] This includes multi-purpose interconnectors and generator-to-user and grid-to-user cables.

systems, merging the functionality of today's separate assets (cross-border interconnectors and radial park-to-shore cables) and optimize the offshore electricity grid. Offshore energy storage systems can help balance electricity supply and demand while minimizing onshore grid congestion. Hydrogen production and transport can both extend the lifetime of existing oil and gas infrastructure as well as help bypass the nearshore spatial competition for electricity cable landings and an already overloaded onshore electricity grid by offering cheaper energy transport. Assessing how to develop such integrated offshore energy systems is highly relevant, since it can improve the overall operational efficiency of the energy system as well as enhance the economic and environmental performance by sharing (parts of) its infrastructure, human capital, products, and knowledge. The studied technologies are deemed promising solutions for the integration of the energy system and are further elaborated in **Chapter 2**.

An interdisciplinary perspective on the development of a more integrated offshore energy system is crucial to comprehensively address the technical, economic, governance and legal aspects of offshore energy systems. Each discipline contributes relevant insights. **Chapter 3** presents how the developed energy system model helps find a cost-effective configuration of an integrated energy system. **Chapter 4** explores the technical feasibility and requirements for development of offshore energy storage systems. **Chapter 5** addresses the institutional frameworks and rules guiding the allocation and coordination of infrastructure components of the offshore energy system. **Chapter 6** navigates the complex legal frameworks regulating offshore energy developments.

Together, this interdisciplinary approach enables unique insights; positioning techno-economic insights within the legal and governance realities shows which technological pathways are most promising, whether its deployment requires regulatory changes and what opportunities and barriers need to be addressed within governance frameworks. Resultantly, seven central recommendations for policy- and decision-makers are formulated in **Chapter 7**.

2| Towards an integrated offshore energy system

Facilitating the large-scale growth of offshore wind energy in the Dutch North Sea the coming decades through the development of the aforementioned offshore energy innovations, will lead to a more integrated offshore energy system. In this project, offshore energy system integration is defined as:

"A coordinated approach to planning and operation of energy generation, transport and storage in the offshore energy system, across multiple energy carriers and sectors."

Current academic literature and projects reports (from industry or applied science) often only implicitly touch upon this concept of system integration, in the form of techno-economic assessments of combining energy generation with specific transport or storage technologies[2]. Particularly, issues of offshore energy system integration from a legal or governance perspective remain largely unexplored. Within the DOSTA project three main components of such integration to support large-scale offshore wind development have been examined: (1) alternative offshore cable connections, (2) offshore energy storage systems, and (3) offshore power-to-hydrogen applications (see Figure 1). Furthermore, DOSTA examined this by also including a legal or governance perspective and thus, followed an explicit interdisciplinary approach. The following paragraphs present the state-of-the-art research on these technologies and, resultantly, emphasize which research gaps are addressed by the DOSTA project.

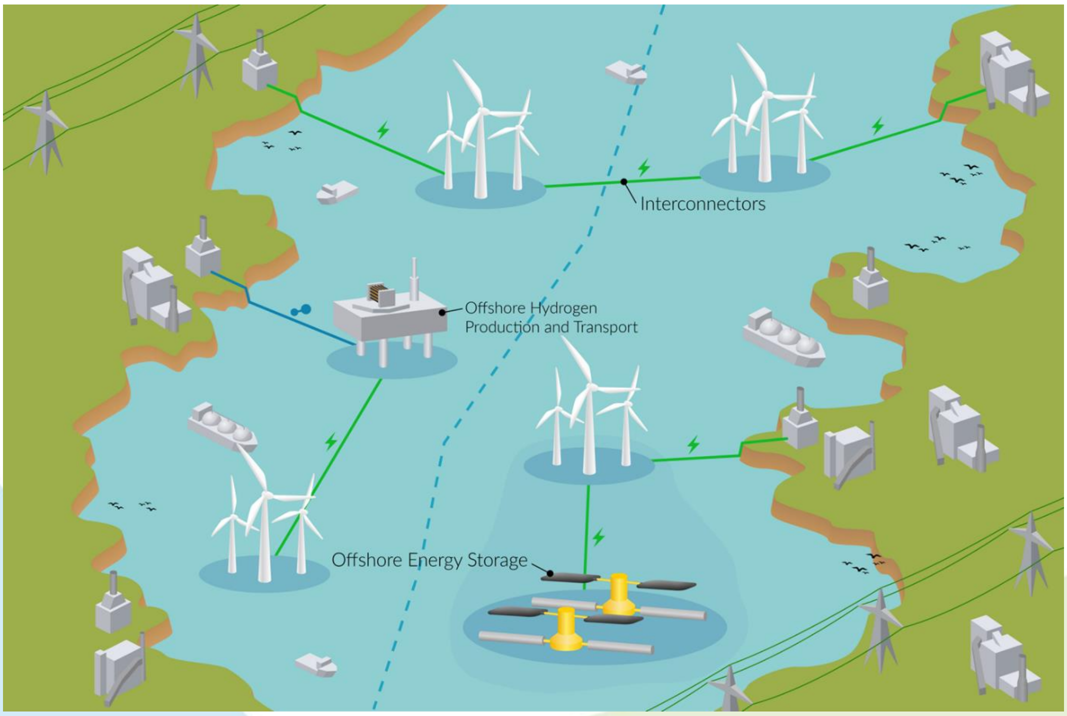


Figure 1 - An overview of the innovative offshore energy technologies studied in the DOSTA project.

[2] See Wiegner, Andreasson, Kusters & Nienhuis, 2024, https://doi.org/10.1016/j.rser.2023.113970.

2.1| Alternative offshore cable connections

The rapid growth of offshore wind farms and their increasing distance to shore requires us to reconsider the ways in which energy can be brought to shore. To date, offshore electricity cable connections are built either as interconnection cables between two different countries (interconnectors) or connection cables to offshore wind farms (park-to-shore cables). Eventually, a meshed grid is expected, combining the functions of interconnectors and park-to-shore cables, for instance by connecting multiple offshore wind farms to various national grids (see Figure 2)[3]. The complexity of such meshed grids further increases when offshore energy storage facilities or other offshore off-takers such as hydrogen producers could be connected to the offshore grid in the future. The development of so-called multi-purpose cables promises higher cable utilization, may reduce energy curtailment and improve electricity exchange between countries.[4] In turn, developing a more meshed grid may stabilize prices, enhance energy security, and reduce carbon emissions.

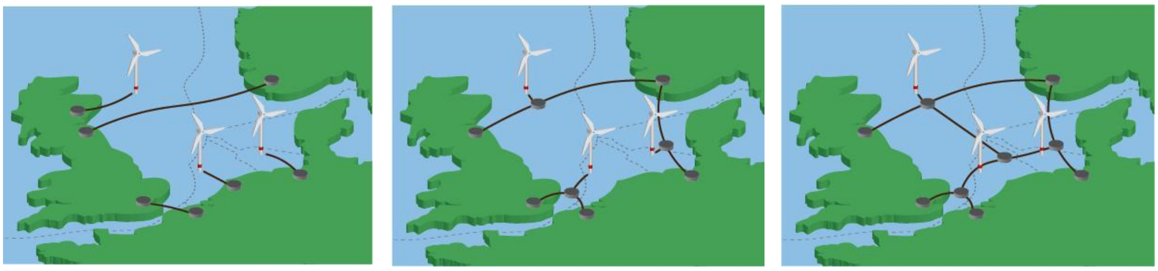


Figure 2 - Potential configurations of the offshore electricity grid. Left: the current system with interconnectors and park-to-shore cables. Middle: offshore wind farms are connected with multi-purpose interconnectors and park-to-shore cables. Right: a meshed grid including multi-purpose interconnector cables and connections to additional offshore off-takers.

To date, cable connections offshore are point-to-point connections, either between two onshore connection points or between a wind farm and the onshore landing points. For long-distance electricity transmission, as is typically the case for both connection types, high-voltage direct current (HVDC) is preferred.[5] This technology has lower electric losses over long distances compared to high-voltage alternate current (HVAC) connections used for the onshore transmission system. However, the implementation of meshed HVDC grids further demands specialized technical components to ensure secure power transfer, comparable to existing HVAC grids.

Planning and governing offshore meshed grids with international connections is complex, requiring cross-border cooperation between governments, transmission system operators (TSOs), wind farm operators, market participants and investors. Current regulatory

[3] See Houghton et al., 2016, http://dx.doi.org/10.1016/j.renene.2016.03.038.
[4] See Spro et al., 2015, http://dx.doi.org/10.1016/j.seta.2014.12.001; Koivisto et al., 2020, http://dx.doi.org/10.5194/wes-5-1705-2020, Houghton et al., 2016, http://dx.doi.org/10.1016/j.renene.2016.03.038; and Hadush et al., 2015, http://dx.doi.org/10.1109/TSTE.2014.2325911.
[5] Houghton et al., 2016, http://dx.doi.org/10.1016/j.renene.2016.03.038; and Elliot et al., 2016, http://dx.doi.org/10.1109/TPWRD.2015.2453233.

frameworks are primarily designed for national contexts. While the potential for a supranational TSO is eminent, national TSOs remain the driving factor in the development of offshore meshed grids. This shift towards an offshore meshed grid (with multi-purpose interconnectors and cable connections to offshore electricity users) calls for careful coordination and balancing of the interests of the various stakeholders. Hence, the DOSTA project delved deeper into how these governance considerations shape the development of alternative cable connections.

2.2| Offshore electricity storage

Energy Storage Systems (ESS) can support the large-scale integration of renewable energy sources in the North Sea region. Integrating ESS into the offshore energy system can increase the overall stability and flexibility of the system by allowing it to store excess available energy and use it when required.[6] Particularly in an interconnected offshore energy system, ESS can provide load balancing services by reducing peak loads and mitigating the impact of intermittency issues on the larger electricity grid.

Several types of ESS can be distinguished and categorized according to the specific working mechanism, application area and technology readiness level (see Figure 3). When looking at a global overview of different energy storage technologies[7], the most promising ESS to be deployed in the North Sea area include offshore battery systems, compressed air energy storage (CAES), synthetic natural gas (SNG) and hydrogen storage, and pumped-hydro energy storage. Developing ESS offshore presents unique challenges and opportunities, requiring careful consideration, since determining the most suitable storage application for each location and required service is inherently challenging. This is especially the case for conventional pumped-hydro storage options, labeled as a mature technology ready to be used, however not applicable for the Netherlands. Other alternative storage solutions such as SNG and hydrogen storage show promise for specific offshore applications, however they remain still in the early development stages.

[6] Spro et al., 2015, http://dx.doi.org/10.1016/j.seta.2014.12.001; Want et al., 2018, http://dx.doi.org/10.1016/j.enconman.2018.07.079; and Ikni et al., 2015, http://dx.doi.org/10.20508/ijrer.v5i4.2657.g6677.

[7] Want et al., 2018, http://dx.doi.org/10.1016/j.enconman.2018.07.079; and International Electrotechnical Commission, 2011, http://refhub.elsevier.com/S1364-0321(23)00828-6/sb56.

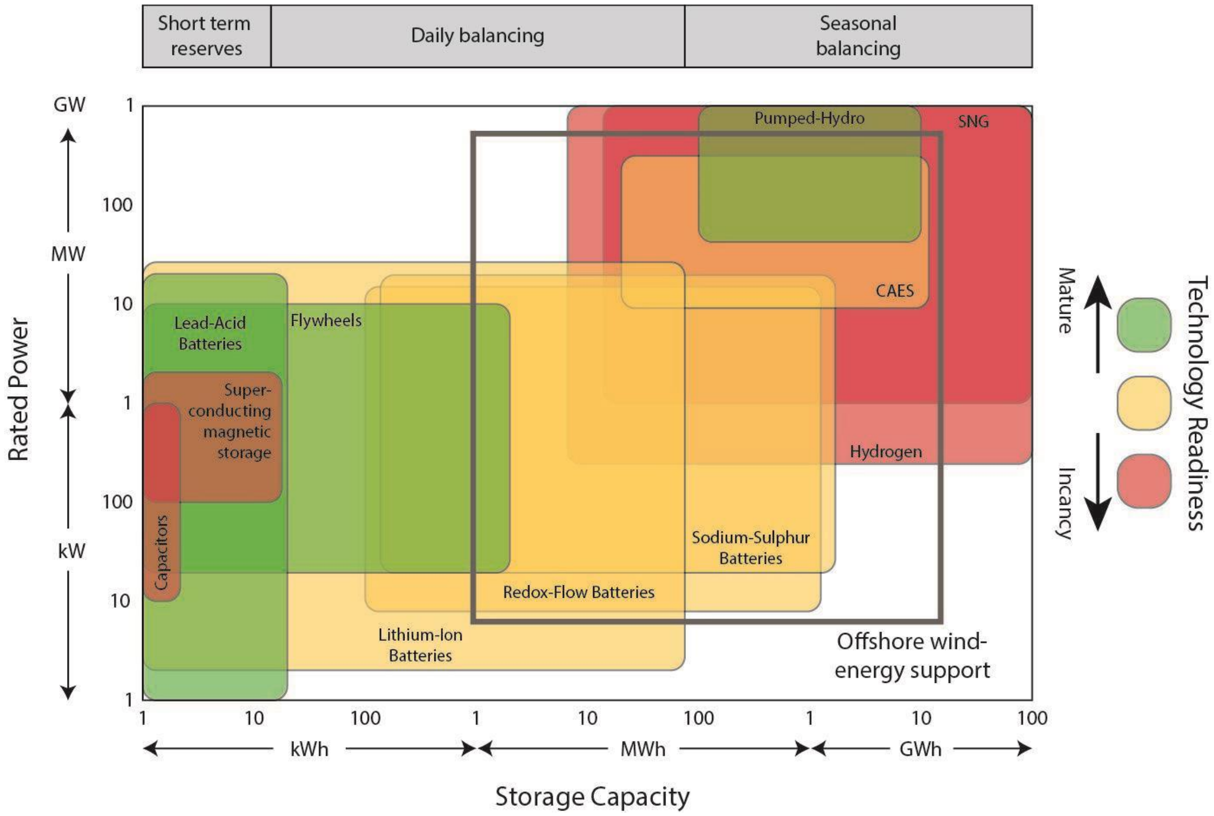


Figure 3 - Several types of energy storage systems categorized according to rated power, storage capacity and technological readiness levels.[8]

To date, there is a general lack of experience with installing and operating ESS offshore. Combined with the uncertainties surrounding the strategic vision of the future North Sea energy system and legal permissibility, financial institutions and investors are reluctant to invest in the development of ESS. Hence, further research is required, not only into the technical and economic feasibility of ESS, but also into the legal and governance considerations shaping decision-making on its development. The DOSTA project particularly focuses on the integration of offshore pumped-hydro storage in the Dutch North Sea energy system. Being the most mature storage technology available, this project highlights the integration of a novel storage concept that enables offshore pumped-hydro storage in the North Sea area. Looking at alternative ways of integrating storage options which are already tested and proven into an offshore environment will cut back precious time in the early development stages and will be an essential element contributing to the energy infrastructure post-2030.

[8] As based on Wang et al., 2018, https://doi.org/10.1016/j.enconman.2018.07.079; and International Electrochemical Commission, 2011.

2.3| Offshore power-to-hydrogen applications

Hydrogen is foreseen to play a significant role in a low-carbon future as an energy storage medium and carrier.[9] Although hydrogen is historically produced using natural gas, connecting it to offshore wind energy enables production of so-called green hydrogen. This type of hydrogen is produced through electrolysis, where electricity is converted to hydrogen using renewable electricity. Producing hydrogen offshore also enables offshore wind farms to be located further from the coastline, given that the costs and energy losses of transporting hydrogen through pipelines are lower than those of transporting electricity by HVDC cables.[10] Nevertheless, the economic feasibility of offshore hydrogen production is debated.[11]

In the DOSTA project, four possible future scenarios for offshore green hydrogen production and transport to shore are considered: (1) centralized onshore production using electricity from offshore wind farms by establishing a direct cable connection (Figure 4a), (2) hydrogen production on existing offshore gas platforms with transport via existing gas pipelines (Figure 4b), (3) production on new platforms with transport via new hydrogen pipelines (Figure 4c), and (4) decentralized production within individual offshore wind turbines (Figure 4d). Scenarios two, three and four reduce the need to lay new power cables to shore and provide the opportunity to convert hydrogen to electricity. Electrification of existing offshore gas platforms for green hydrogen production has been widely investigated and can help reduce emissions and extend the economic lifetime of the infrastructure[12]. As such, future scenarios for offshore (green) hydrogen production, storage and transport involve the integration of three offshore energy subsystems: offshore wind, offshore gas, and offshore hydrogen infrastructure. This presents a clear departure from the previously common sectoral approach to regulating and governing the offshore area. Hence, more understanding and research are required into the extent to which current legal frameworks, policies and decision-making processes enable its development and cross-sectoral considerations.

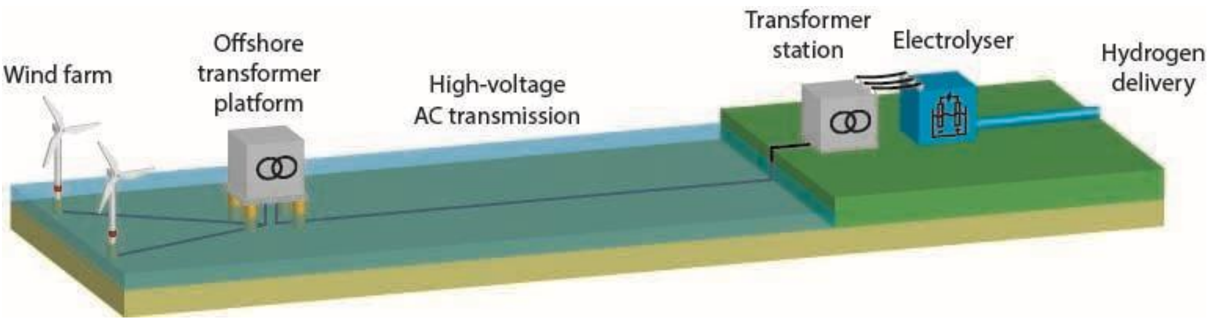
[9] See the EU Strategy on Hydrogen, 2020; and the Dutch government's Roadmap for Hydrogen, 2022.

[10] See Yan et al., 2021, http://dx.doi.org/10.1016/J.ENCONMAN.2021.114690; Martínez-Gordon et al., 2022, http://dx.doi.org/10.1016/j.adapen.2022.100097; Peters et al., 2020, http://dx.doi.org/10.4043/30698-ms.

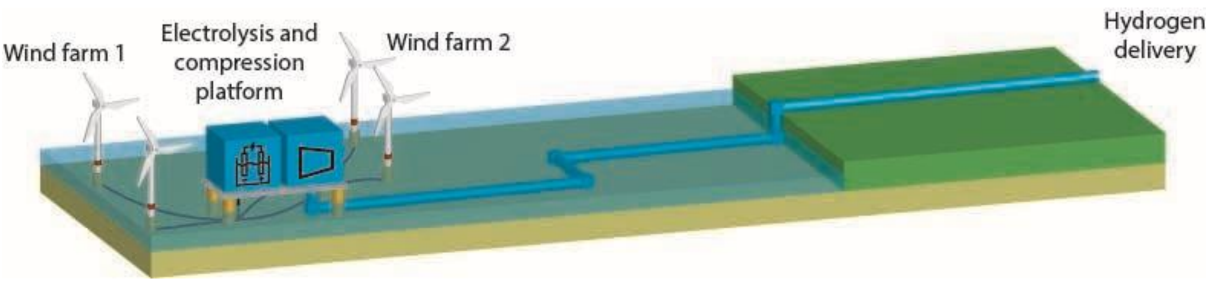
[11] See Singlitico et al., 2021, http://arxiv.org/abs/2104.04151; Jang et al., 2022, http://dx.doi.org/10.1016/J.ENCONMAN.2022.115695; and Wu et al., 2022, http://dx.doi.org/10.1016/J.ENERGY.2021.122077.

[12] Zhang et al., 2021, http://dx.doi.org/10.1016/j.jclepro.2021.126225; Spezakis and Xydis, 2022, http://dx.doi.org/10.1007/S11356-022-23292-2/METRICS; Riboldi et al., 2021, http://dx.doi.org/10.3390/EN14238123; and Wu et al., 2020, http://dx.doi.org/10.1155/2020/8820332

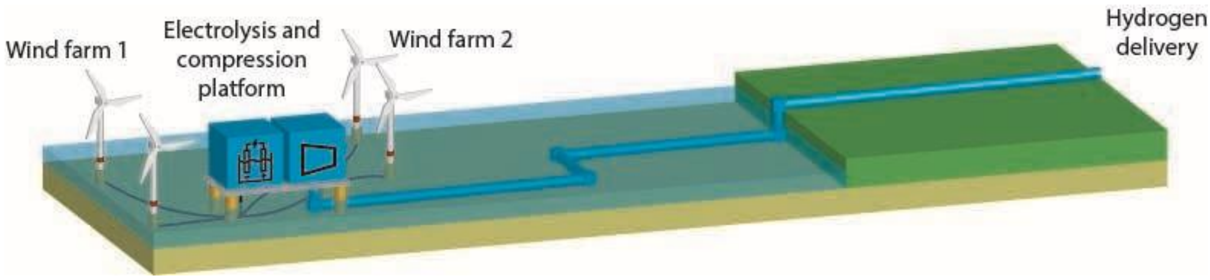
Figure 4 – Pathways for hydrogen production from offshore wind.



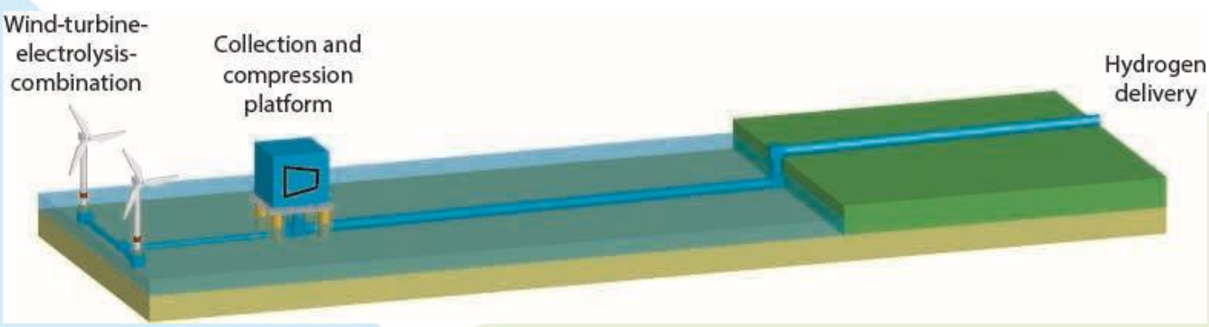
(a) Scenario 1: Onshore hydrogen production. Electricity transmission can be implemented with any of the technologies presented in the previous section (i.e., AC or DC)



(b) Scenario 2: Distributed electrolysis and compression on existing oil and gas platforms. Transport pipelines are repurposed from existing oil and gas infrastructure.



(c) Scenario 3: Centralized electrolysis and compression on a new platform or artificial energy island. Transport through newly constructed hydrogen pipelines.



(d) Scenario 4: In-turbine electrolysis with a collection and compression platform. Platforms and pipelines can be newly constructed or repurposed.

3| Optimizing the Energy System

Energy system models can help to understand the role of the three innovative energy technologies for a successful integration of large-scale offshore wind in an international context. Hence, not only the Dutch part of the North Sea, but also other neighboring states (United Kingdom, Norway, Denmark, Belgium, The Netherlands, and Germany) were modeled for the year 2030 and 2040 (see Figure 5).[13] Each country is divided into multiple onshore and offshore nodes to capture grid congestion. Each node has a specific electricity and hydrogen demand, which are met through a mix of renewable, conventional, and hydro storage technologies as well as grid exchanges with neighboring nodes.

[13] See https://zenodo.org/records/13384688 for the model used.

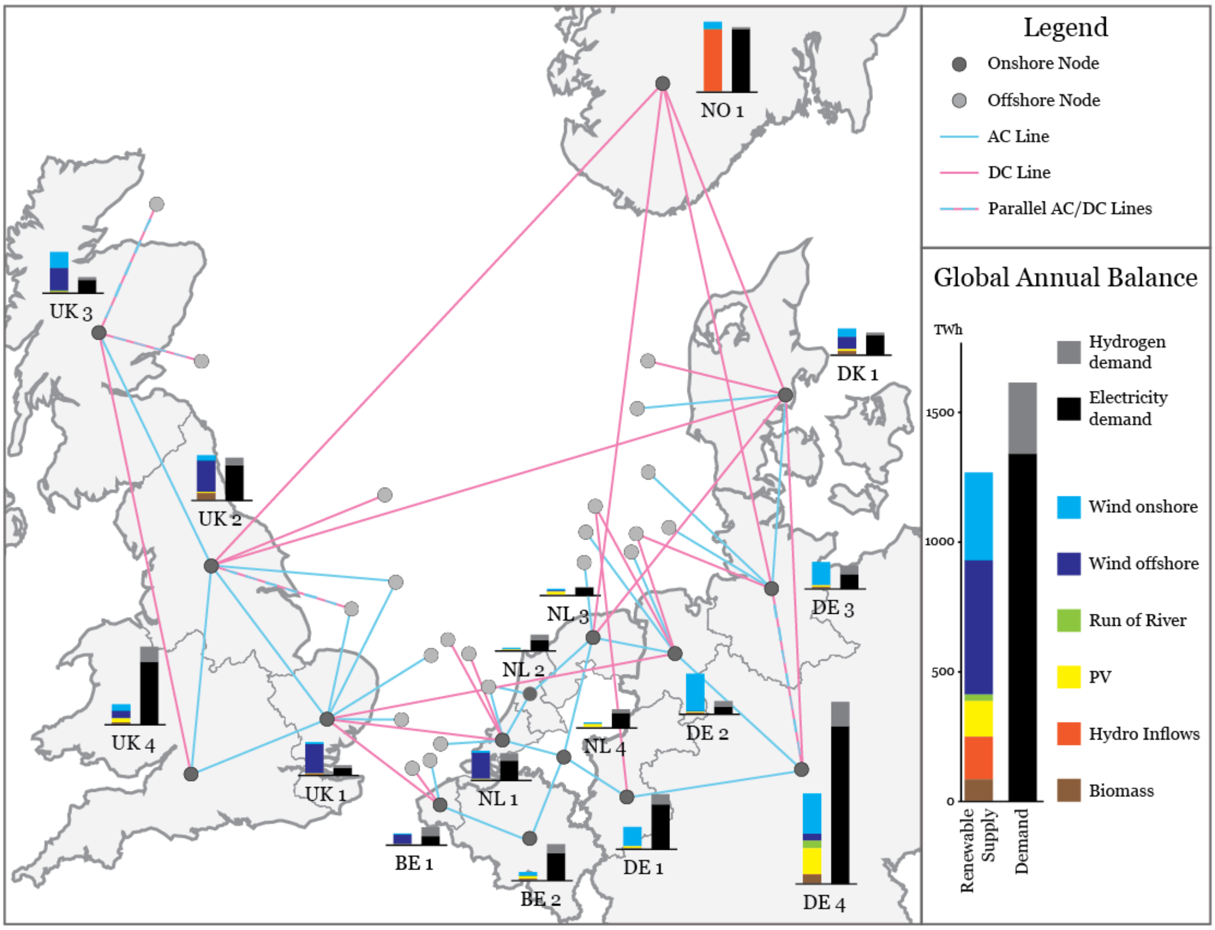


Figure 5 - Illustration of the topology of the reference energy system. The vertical bars show the annual sum of theoretical supply of renewable resources without curtailment in comparison to annual demand at the same node as projected for the year 2030. Hydro inflows refer to natural water inflows into the upper reservoir of pumped hydro storage plants

The model uses capacity projections for 2030 from ENTSO-e's 2021 Annual Report National Trends scenario, incorporating anticipated expansions in electricity generation capacities and grid infrastructure. The Reference scenario optimizes current system operations without additional capacity or grid expansion. Three other main scenarios evaluate the three strategies for offshore system integration: cable connections, energy storage, and hydrogen production and its storage. These scenarios co-optimize system design and operation, utilizing existing infrastructure. The model operates with hourly resolution to accurately reflect renewable generation fluctuations, demand variations and storage needs. The model can be used to look at two different perspectives: the role of the three innovative technology pathways to reduce total system cost and their role to reduce emissions. Total system costs are calculated as the sum of operational costs from existing technologies and investment into innovative technologies of the three integration measures. Total emissions depict the sum of emissions from conventional electricity generation technologies and emissions from blue hydrogen production.

The Reference scenario was optimized to minimize total system costs. Thereafter, each of the three strategies for offshore system integration was optimized. At last, all three innovative pathways were optimized together, as depicted in the *Synergies* scenario. The results are shown in Figure 6 and 7.

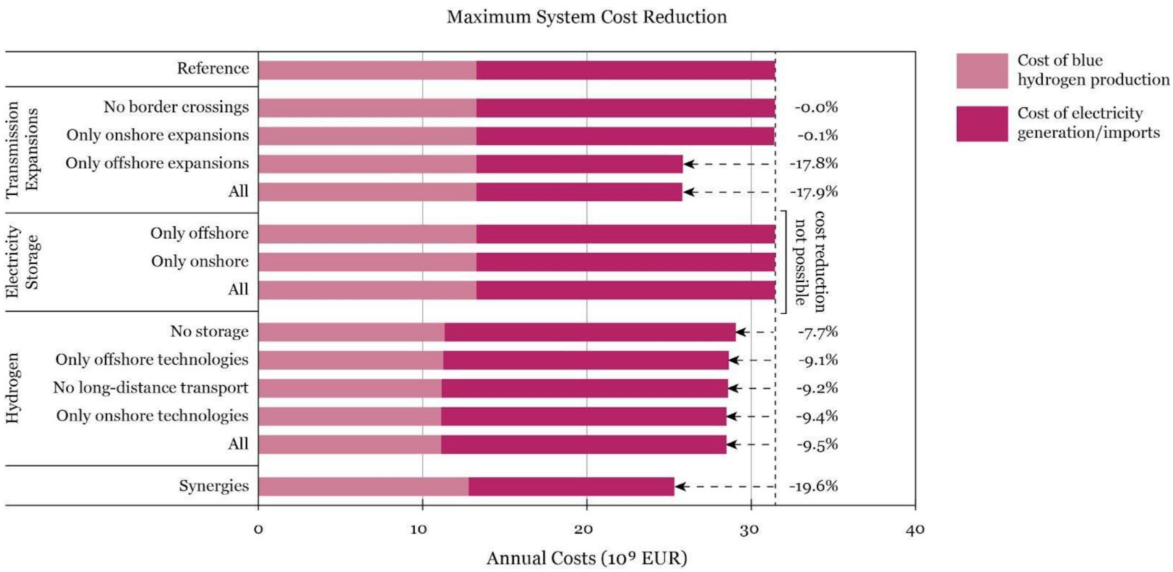


Figure 6 – Cost reduction potential of integration measures

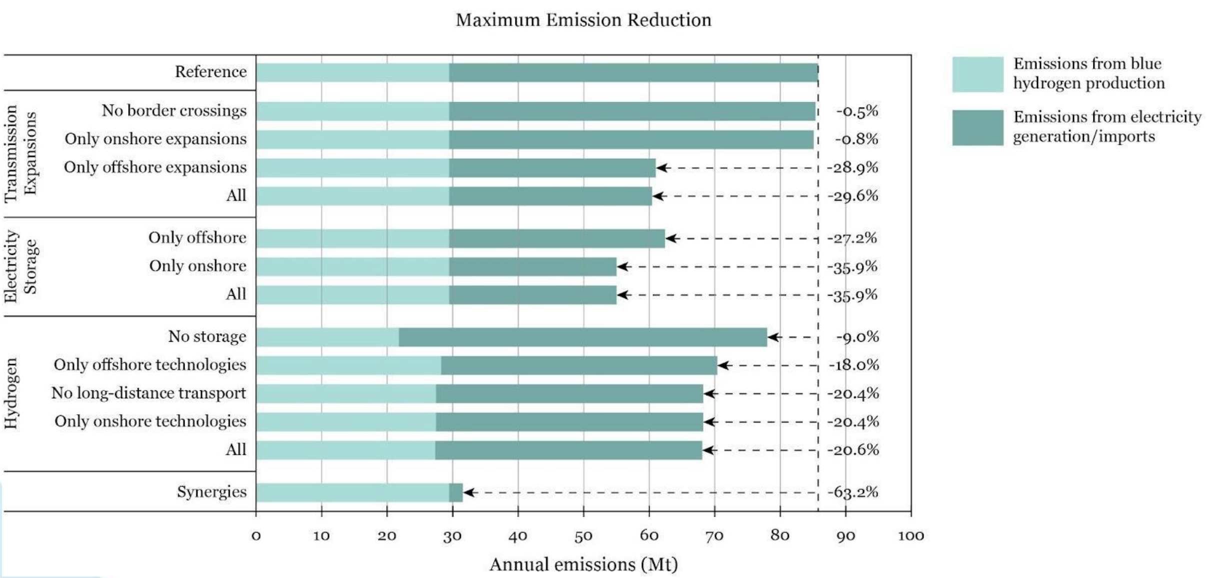


Figure 7 – Emission reduction potential of integration measures

3.1| The potential of electricity grid expansions by 2030

The results show that allowing for an expansion of the electricity grid beyond the plans for 2030 can significantly contribute to emission reductions and cost savings. If all transmission corridors, including offshore, can be expanded, emissions could be reduced by up to 30%

compared to the Reference scenario (Figure 7). Note that this is solely a result of an expansion of electricity transmission, and that electricity generation capacities and hydro storage capacities are the same as in the Reference scenario. However, restricting the allowed expansion corridors to onshore corridors only, both the cost reduction and emission reduction potential are less than 1%. As such, high system cost and emission reductions are only possible if offshore and cross-border transmission expansions can materialize. Notably, the cost-optimal scenarios involve new offshore connections, primarily between Norway and other countries, leveraging Norway's hydro resources for large-scale emission and cost reductions. As stressed in Chapter 5, this would require appropriate governance frameworks for intensified international collaborations and potential remuneration. These offshore connections also facilitate wind farms serving multiple onshore nodes. As such, the key takeaways are:

- Investing in cross-border interconnections across the North Sea is crucial for reducing system costs and emissions.
- The current onshore transmission grid is adequate for integrating projected renewable generation by 2030, though minor cross-border expansions offer additional benefits.
- Forming simple meshed grids offshore by interconnecting wind farms is essential for reducing both costs and emissions. This also enables wind farms to serve multiple onshore nodes.

3.2| The potential of electricity storage by 2030

Allowing for additional electricity storage shows a significant potential for emission reduction in the power sector (around 35%; Figure 7), surpassing the reduction potential of grid expansions. However, the cost of achieving high emission reductions through electricity storage is extremely high. For instance, achieving just a 1% emission reduction through storage costs approximately 650 EUR/t.

To reduce emissions, onshore storage is particularly effective, while offshore storage alone offers limited benefits due to fewer storage locations and insufficient transmission capacity to major demand centers. Allowing electricity storage to be installed only offshore (1) is more expensive compared to locating it onshore and (2) also shows a lower emission reduction potential than its onshore counterpart. The key findings are:

- Electricity storage offers significant emission reduction potential for the power sector.
- Despite its effectiveness, storage is an expensive emission reduction strategy.

- However, leveraging "free" flexibility measures like demand-side management or vehicle-to-grid could provide similar benefits without additional investments. For example, utilizing half of the battery capacity of 10 million electric vehicles could achieve a 10% emission reduction without additional investment costs

3.3| The potential of hydrogen by 2030

The integration of hydrogen production, storage, transport, and reconversion into electricity offers significant emission and cost reduction potential. To lower emissions, hydrogen needs to primarily serve as a storage medium, and scenarios allowing hydrogen storage show nearly double the emission reductions compared to those without it. To lower total system costs, however, it is best to use carbon-free hydrogen directly to replace blue hydrogen. The cost optimal scenario (Figure 6) sees a 46 TWh production of carbon-neutral hydrogen, covering around 16% of 2030 demand. Onshore hydrogen production and use are more effective than offshore due to lower costs and greater flexibility. As such, offshore-only hydrogen production leads to higher costs and reduces the emissions that can be avoided compared to onshore hydrogen production.

As emission reduction targets rise, storage and reconversion of hydrogen becomes increasingly important, with needs for reconversion to electricity growing significantly. Beyond a 10% reduction target compared to the Reference scenario, the capability of natural gas power plants to mix hydrogen into the fuel is insufficient, necessitating additional fuel cells. The key findings are summarized as follows:

- Hydrogen is a versatile energy carrier that can function as a storage medium, transport method, and natural gas replacement.
- In cost-optimal scenarios, hydrogen is mainly used for direct replacement of carbon-emitting fuels, reducing costs and emissions.
- As emission reduction targets increase, hydrogen storage's importance for balancing energy systems grows.
- In all scenarios, carbon-neutral hydrogen production relies on a mix of nuclear and renewable sources, reducing curtailment of renewable electricity generation and increasing nuclear plant capacity factors.

3.4| Synergies between all integration pathways

In the Synergies scenario, all three strategies for offshore system integration – transmission expansion, electricity storage, and hydrogen technologies – are available. The analysis reveals that no individual technology can maximize emission or cost reduction with the projected 2030 renewable capacities, highlighting the importance of combining multiple approaches.

For the highest emission reductions (Figure 7), a combination of transmission line expansions and electricity storage is optimal, enabling both inter-regional and inter-temporal balancing. Inter-regional balancing is favored due to lower transmission losses compared to storage processes. To reach the highest possible emission reduction, hydrogen technologies are not necessary.

For the highest cost reductions (Figure 6), a mix of transmission expansions, electrolysis, and hydrogen storage is most effective. The required transmission expansions are mostly offshore, forming a meshed grid in the North Sea, while green hydrogen serves to replace blue hydrogen and provide supplementary storage. Approximately 5.4 GW of electrolysis capacity is needed, primarily in the UK, powered by nuclear and renewable sources. Most of the cost reductions, however, are due to an expansion of the electricity grid across the North Sea (cost reduction of around 18%). Hydrogen production, storage, transport, and reconversion can only contribute another 1,7%, suggesting that grid expansions are much more crucial than hydrogen technologies. The key findings of the modelling work are summarized in Figure 8.

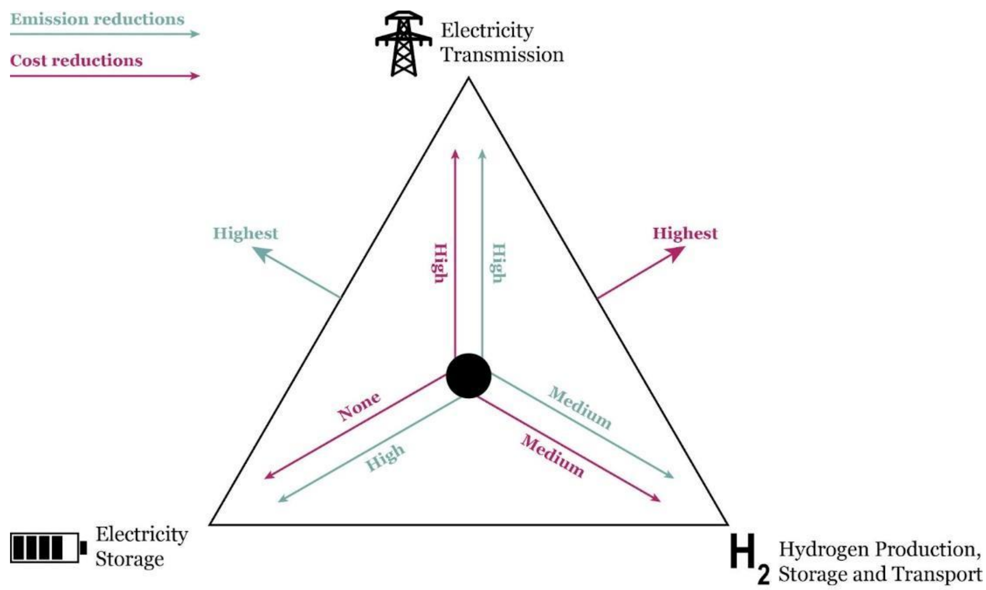


Figure 8 - Emission and cost reduction potential of the three strategies for offshore system integration.

The key take-aways for the Synergies scenario include:

- Maximum emission reduction requires both grid expansion and increased electricity storage; hydrogen technologies have no impact on this potential.
- The greatest cost reductions are achieved through grid expansions, with minor additional savings from producing carbon-neutral hydrogen to replace blue hydrogen.
- Expanding the electricity grid across the North Sea is a no-regret measure, reducing both costs and emissions.

4| Technological Challenges for Storing Energy Offshore

To explore the technical feasibility of storing energy offshore, the DOSTA project researched a novel offshore pumped-hydro energy storage technology, known as the Ocean Battery, as a promising solution for a more integrated offshore energy system in the North Sea area. This storage technology uses the hydrostatic pressure of the surrounding seawater to store potential energy that can be transformed into electricity via hydro-turbines and transmitted to the grid later. The following sections highlight the results of research on the round-trip efficiency of the Ocean Battery (Section 4.1), the impact of external loading and green mechanics in a submerged environment (Section 4.2), and a proposed digital twin model framework for the internal operation of the system (Section 4.3).

4.1| Determining the round-trip efficiency

Conventional pumped hydro storage (PHS) is a well-established technology with a round-trip efficiency (one full cycle of capturing-storing-releasing energy by means of a pump-turbine system) of 65-85%, making it one of the most efficient energy storage technologies.[14] The proposed novel offshore PHS differentiates from conventional PHS by being deployed under water and consequently features novel design elements required for a closed operating system. The Ocean Battery system is located on the seabed to fully utilize the hydrostatic pressure of the surrounding seawater to store the energy. Different location-specific designs have been proposed for both shallow-water locations (30-100 meters operational depth), which is relevant for the North Sea area, and deep-sea locations (>100 meters operational depth) which both store energy according to the same working principles (Figure 9).

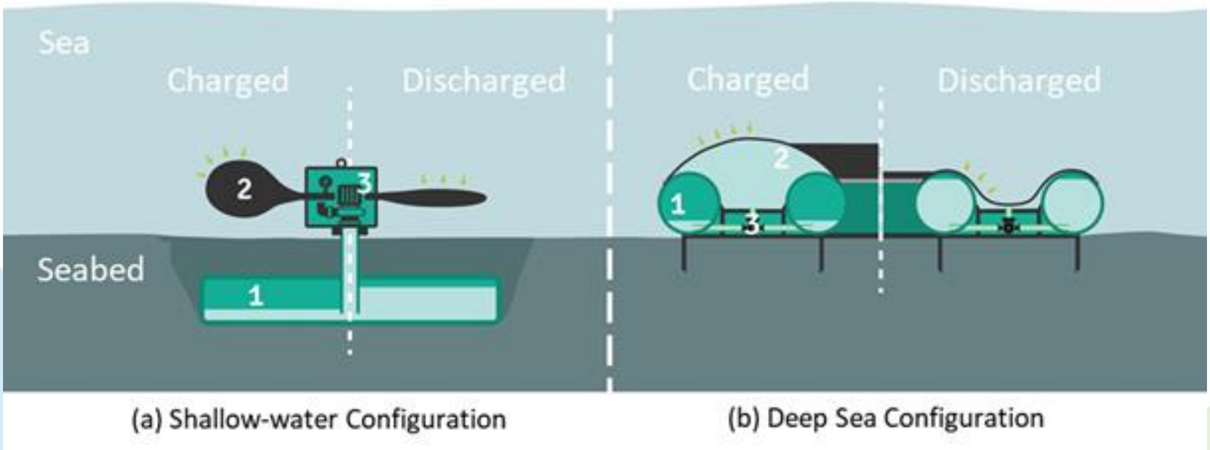


Figure 9 - Location specific design configurations of the Ocean Battery

To validate the working principle of the Ocean Battery, a small-scale prototype was deployed at the Eemshaven Seaport in Groningen. The results of the experimental measurements

[14] See T. M. Letcher (Ed.), 2022, pp. 147–175. https://doi.org/10.1016/B978-0-12-819727-1.00079-0.

showed the pressure losses of the system during a charging and discharging cycle. An analytical framework was proposed to capture the internal dynamics together with the diverse types of energy losses in the system. By combining the experimental measurements and the proposed analytical model, the round-trip efficiency for the novel energy storage system was calculated. The key findings of the foundational model framework are:

- The calculated pressure losses in the analytical model framework are confirmed by the experimental results of the small-scale prototype, validating the working concept of the proposed energy storage solution.
- The novel design features of the Ocean Battery system, such as the flexible bladder and the umbilical line have a minimal impact on the overall energy losses in the system.
- The measured pressure losses in the hydraulic system account for 2-4% of the total losses for one charging or discharging cycle and are predicted correctly by the validated analytical model.
- The total round trip efficiency for the Ocean Battery system is determined to be within a 65-85% efficiency performance range comparable to established technologies such as conventional PHS.

4.2| External loading factors and green mechanics

When deploying an underwater ESS in the North Sea, different impact factors are to be considered. External loading factors acting on the system's structure and material degradation can influence operational performance over its lifetime. Three main external loading factors are identified for a submerged system in the North Sea: (1) the impact of marine biofouling and sand deposition on the flexible bladder, (2) dynamic loading induced by a combination of waves, swells, and tides, and (3) local scouring which impacts the stability of the foundation. Small-scale lab experiments were performed at the RUG together with experimental measurements at the Groningen Seaport of Eemshaven for incremental time periods on submerged samples of the flexible membrane element of the proposed Ocean Battery. The surface degradation of these samples was determined by measuring the change in surface topology using a profilometer. The main takeaways are:

- The impact of marine biofouling can be described as a complex development over time influenced by different independent factors such as depth, salinity, zonal location, and local composition.
- Being able to predict marine biofouling composition and development is especially important for the novel elements introduced in the system, such as the flexible bladder and umbilical line.

- Especially mollusks species, such as mussels, scrape the surface resulting in pitting of the surface material over time.
- Further testing of the cut-out samples shows a decrease in the strength and increase in the overall flexibility of the material, most likely due to the exposure of fillers, such as calcium carbonate, at local delaminated surface locations.

In addition to the experimental results, a continuous simulation model approach helped determine the impact of scouring on a deployed Ocean Battery system. Specifically, the morpho-dynamic parameters from the *Hollandse Kust West* offshore wind farm plot on the Dutch North Sea were used. The scouring behavior was determined by a sediment transport model fully coupled to sea state and ocean wave data. The impact of environmental loading on the system's behavior is expanded by translating different sea states into a dynamic pressure source using linear wave theory. Combining the results of these simulations, the key findings are as follows:

- Immediate scour development patterns are identified and can develop significant seabed elevation changes over time along the profile of the Ocean Battery system.
- Scour protection design measurements must be considered when installing shallow water design in the North Sea region.
- The type of waves the system is exposed to depends on the system's depth of deployment, where deep-water, shallow-water and intermediate wave regimes are identified.
- Environmental loading due to waves and scouring affects the dynamic behavior of the system. Preliminary results indicate an overall operating head and efficiency deviation of 2-4% due to combined loading during charging cycles.

4.3| A digital twin model for the performance of pumped-hydro energy storage

The Ocean Battery system is described by (1) a physical system, representing the actual device, (2) a cyber-system that describes the internal operating and control mechanisms and (3) a digital twin system which is used as a tool merging the various sources of complex data in a uniform model to simulate the actual behavior of the system (Figure 10).

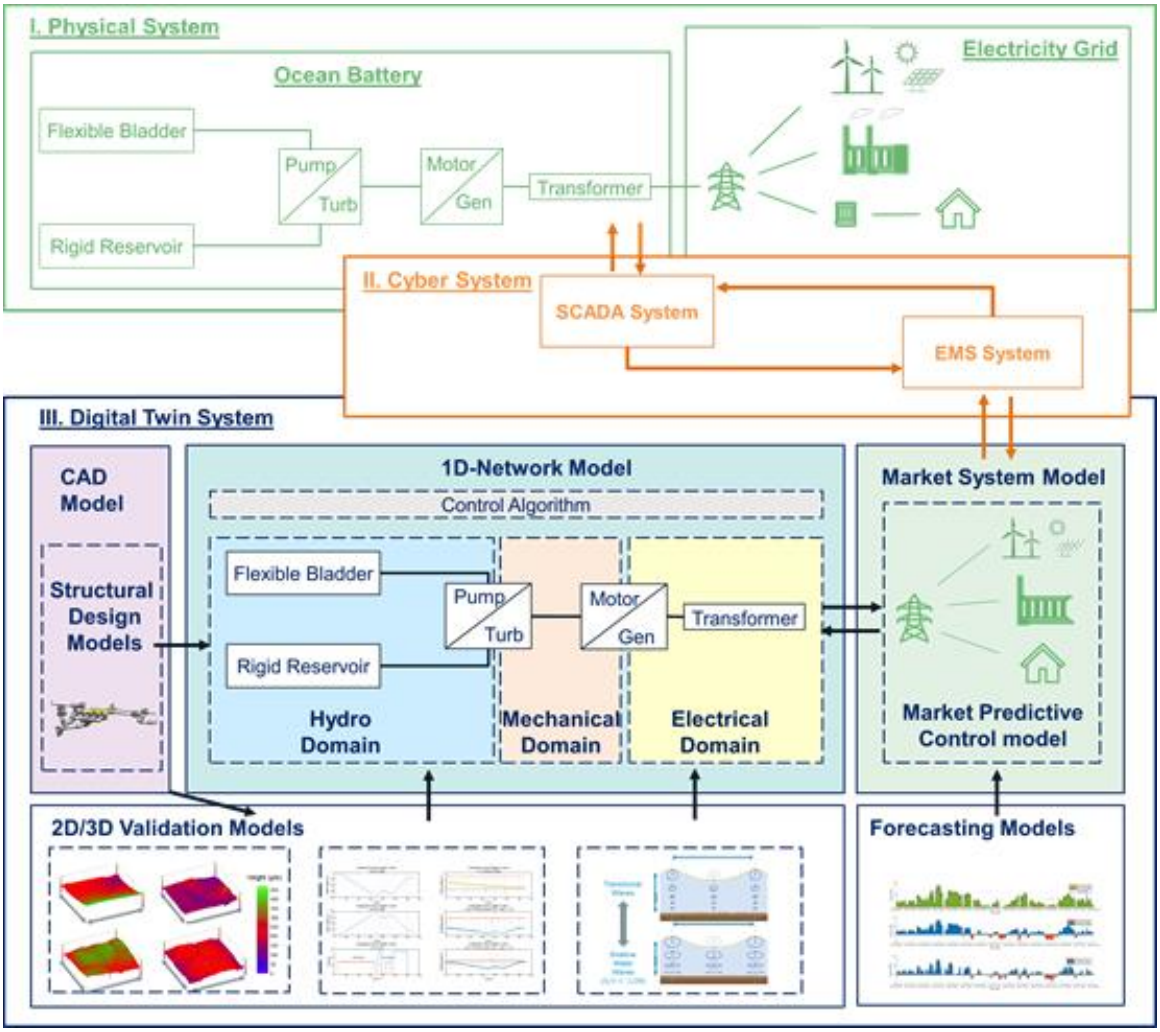


Figure 10 - A digital twin model framework describing the internal operation and dynamics of the Ocean Battery System.

The complexity of the digital twin model is reduced through a so-called reduced order method approach since this is deemed the most efficient way to analyze the complex performance behavior when integrating a novel PHS into an offshore energy system. These subsequent steps culminated in a model that can be used to extract the performance behavior of a novel PHS under different scenarios.

The key takeaways for this approach are:

- An electrical analogy approach is integrated into the digital twin model to enable the coupling of complex behavior between the electrical, mechanical, and hydro domain of the system into one overarching reduced order water-to-wire model.
- The reduced order approach provides a universal approach in accurately describing the internal pump and turbine dynamics during part-load operation of the Ocean Battery in a larger offshore energy system.

- The reduced order model captures the dynamic behavior of the complex interaction between the pump and turbine efficiency for different guide vane operations, which enables the system to be optimized under system control operations contributing to the overall performance and round-trip efficiency.

Being able to clearly define the internal dynamics during operation enhances the capabilities in predicting and controlling the system, enhancing its overall performance and stability. This is especially impactful for novel ESS where the aim is to be able to account for and minimize the energy losses and to optimize its operational efficiency.[15]

[15] See Nienhuis et al., 2023, https://doi.org/10.1016/j.est.2023.109374.

5| Marine Spatial Planning for offshore energy system integration

Planning and governance are essential parts of developing a more integrated offshore energy system. This is not only about strategic decision-making for desirable futures, but also to establish enabling rules, regulations, and practices as well as to find suitable locations for new activities or infrastructures.

Following the 2014 EU Maritime Spatial Planning Directive, governments across Europe have adopted Marine Spatial Planning (MSP) as an instrument to consider the various sectoral interests and coordinate decisions for the sustainable use of marine areas. Previous research[16] has shown that renewable energy developments – most notably offshore wind energy – are a key driver of MSP processes and consequently considered a priority in resulting marine spatial plans. In the Netherlands, the Program North Sea 2022-2027 presents the marine spatial plan for the Dutch part of the North Sea (see Box below and Figure 11).

The Program North Sea 2022-2027

With the Program North Sea 2022-2027, the Dutch national government sets the frameworks for spatial use of the North Sea in relation to the status of the marine ecosystem, and for the policy aimed at improving the environmental status. As such, it outlines the main priorities and spatial claims present in the Dutch Exclusive Economic Zone (EEZ) of the North Sea. Five main challenges are specified for the Dutch North Sea: the nature transition, the energy transition, the food transition, coherence and balance, and a sustainable blue economy. The Program proactively reserves offshore space for the following activities and uses: offshore wind energy, nature protection, sand extraction, shipping, cables and pipelines, and military areas (see Figure 11).

This Program is established under the responsibility of the Minister of Infrastructure and Water Management, the Minister of Agriculture, Nature and Food Quality, the Minister for Nature and Nitrogen Policy and the Minister for Public Housing and Spatial Planning, in consultation with the Minister for Climate and Energy.

5.1| Formulating new marine spatial plans

According to the EU MSP Directive, new marine spatial plans must be developed at least every 10 years. These plans can include zoning regulations, spatial reservations for new activities, and broader policies guiding decision-makers in how they should address offshore developments. Offshore hydrogen production, alternative cable connections or offshore energy storage were not explicitly addressed in the previously Dutch marine spatial plan. The development of the new Program North Sea 2022-2027 presented a unique opportunity to explore what opportunities and barriers shaped the uptake and prioritization of these innovative offshore energy technologies in new policy.

16 See Jones et al., 2016, https://doi.org/10.1016/j.marpol.2016.04.026; and Spijkerboer et al., 2020, https://doi.org/10.1016/j.marpol.2020.103860.

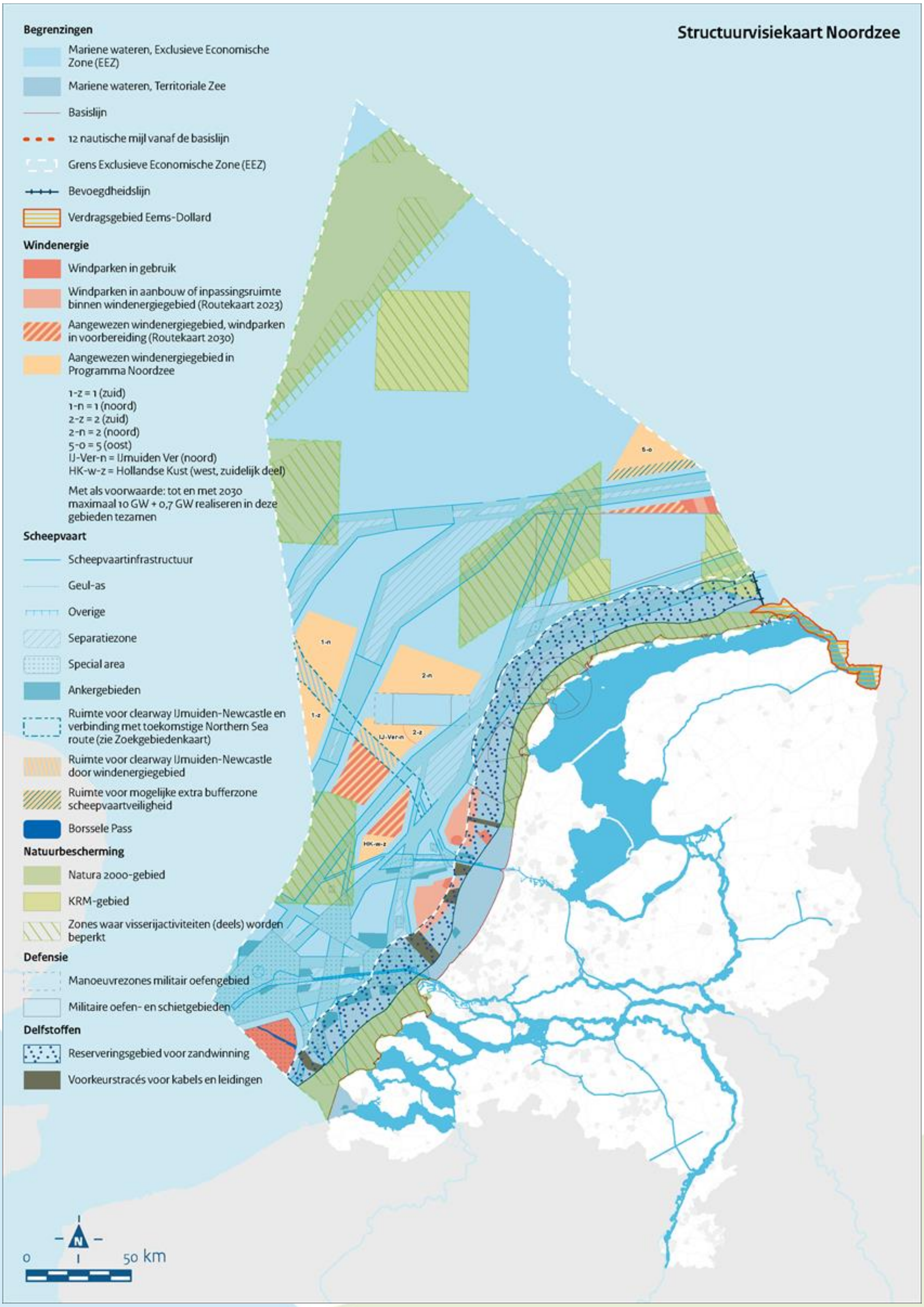


Figure 11 - The Dutch marine spatial plan

The results show that Dutch MSP processes may support the prioritization of offshore energy technologies through the **multitude of opportunities for stakeholder engagement** and **existence of stakeholder networks**. Also, an established group of actors exists with a long history of offshore activities and highly valuable informal connections with relevant policymakers. These include oil and gas producers, who have been of great economic importance to the Netherlands historically, and offshore wind energy developers, who are seen as crucial actors to decarbonize the Dutch energy system. These close relations enable industry interests and considerations to be accounted for in new plans and policies. The results show a greater receptivity to these interests with interviewed policymakers, who acknowledge a dependence on the technical expertise within industry actors. As such, stakeholders' perceptions of the innovative offshore energy technologies partly explain how they become prioritized within plans and policies (see Box below).

Stakeholder perceptions on innovative offshore energy technologies

Stakeholders position **offshore hydrogen production** as an important, one-fits-all solution for the energy system. As such, producing hydrogen offshore is positioned as a no-brainer, since we'll always find a use for it anyways. Further, the popularity of hydrogen can be explained by its direct linkages to existing oil and gas infrastructure. Using existing pipelines or offshore platforms to, respectively, transport or produce hydrogen offshore presents an economically attractive pathway for greening the energy supply. This can also extend the lifetime of existing infrastructure and push back decommissioning efforts.

Perceptions on **alternative cable connections** show a collective understanding of desirability and technical feasibility. However, since responsibilities for development and ownership are not formally assigned by law, further action or prioritization in the Dutch plan remains limited.

The technical feasibility and regulatory unclarity surrounding **offshore energy storage** are questioned. Nevertheless, the Dutch approach to tender procedures for the *Hollandse Kust West* and *IJmuiden Ver* offshore wind farms show a notable exception. Including requirements for investments related to 'system integration' shows direct policy action to incentivize the development of energy storage infrastructure.

At the same time, various barriers hinder the role MSP processes can play in prioritizing offshore hydrogen production, alternative cable connections and offshore energy storage:

- **Close government-industry relations**

Close and dependent relations between policy- or decision-makers and industry actors risk that powerful actors with established governmental connections hold greater influence over MSP processes than starting developers of new innovative technologies. This may also explain the popularity of offshore hydrogen production compared to offshore energy storage and interconnectors, who lack a direct connection to regime actors who may legitimize prioritization.

- **Short-term fixation and tunnel vision on OWE development**

The development of offshore energy storage, alternative cable connections and offshore hydrogen production are all perceived as long-term (post-2030) solutions. However, Dutch MSP processes follow a six-year timeline (the plan is in effect until 2027) and great priority lies with achieving carbon reduction and OWE targets by 2030. This raises immediate concerns: due to the lengthy development timelines of offshore infrastructure and uncertainties in project advancement, further demonstration projects and robust institutional frameworks are necessary to support and justify long-term investment decisions. This includes supportive regulatory frameworks, as further elaborated in Chapter 6.

- **Great uncertainties surround and are inherent to innovation**.

Many unclarities still exist in regulatory frameworks, market structures and financial support mechanisms. In response, a variety of research programs[17], stakeholder networks[18] and subsidy structures[19] are established to incentivize further knowledge development. Interviewed industry stakeholders call for clarity and long-term certainty in regulations and policy. Nevertheless, a proactive consideration of these technologies is on hold due to the risk-averse and safety-first attitude dominant within Dutch MSP processes. What industry stakeholders and academic experts consider of greater value is to 'start doing,' but the risk-averse and safety-first attitude embedded in planning and permitting processes postpones the development of (large-scale) demonstration projects. A complex tension arises; on the one hand, knowledge gaps limit policymakers' ability to anticipate future developments, on the other hand, knowledge development itself is hindered by the wish to regulate all before 'putting something in the water.'[20] This may also pose a threat to the Ocean Battery presented in Chapter 4, which requires further technical development to confirm technical feasibility in the harsh offshore environment.

5.2| Integrating environmental considerations into decision-making

When formulating plans, European and national legislation stipulates that Strategic Environmental Assessments must be carried out when plans are likely to have significant environmental effects. An SEA provides a policy tool helping decision-makers to identify potential (long-term) environmental consequences of proposed plans and integrate them

[17] WOZEP; De Rijke Noordzee; North Sea Energy; PosHYdon; H2Gateway; HyWay27; TSO2020
[18] Community of Practice North Sea; North Sea Dialogues; Nexstep; ElementNL
[19] TKI Energie; SDE++; HER+; DEI+; Horizon2020; Connecting Europe Facility; Interreg
[20] See Kusters et al., 2023, https://doi.org/10.1016/j.eist.2023.100705.

during plan formulation. Both SEA and MSP aim to strengthen the environmental component of planning processes and to facilitate a strategic and proactive decision-making practice.

Including environmental considerations in decision-making is also important for the development of offshore energy storage and transport alternatives. Namely, finding the optimal configuration of a more integrated energy system relies not only on its techno-economic feasibility (Chapter 3 and 4), but must also consider the wider environmental effects of its spatial allocation. Based on case studies of SEA for MSP in Belgium, England, Germany and the Netherlands,[21] the research shows that integrating environmental considerations into the formulation of a marine spatial plan is compromised in two ways.

- **Data and understanding on the marine environment are limited.**

Assessing cumulative effects is a central element of an SEA. Namely, having a complete picture of the effects resulting from the combined influences of various human activities and natural processes on the total marine environment enables decision-makers to strategically steer allocation of activities or development of infrastructure. However, available data predominantly centers around species and habitats protected under the EU Birds and Habitats Directives and the Natura 2000 framework. Beyond the availability of data, it is also important to consider how these scientific results of SEAs are translated into practice. For example, the lengthy nature of SEA reports and issues of understaffing complicate how SEA results find their way into the marine spatial plans. Hence, more attention should be paid to the science-policy interface shaping how environmental considerations find their way into decision-making processes.

- **Alternative approaches to reach policy goals are minimally explored**.

Ideally, SEAs offer a strategic instrument to explore the environmental implications of various policy options and choose (or at least present to decision-makers) the most environmentally-friendly option. Scholarly work on SEAs, therefore, highlights the importance of formulating alternative futures to be compared. In the case of marine spatial plans, this would imply the development of alternative perspectives upon the spatial allocation of offshore uses and activities and the exact activities considered. In practice, however, exploring alternatives holds only a minimal role in SEAs conducted for marine spatial plans. For example, the Dutch Program North Sea primarily brought together existing sectoral policies that had clearly delineated spatial choices in them already. Consequently, there was limited flexibility to develop and assess alternative approaches which did not fit with these existing policies. Overall, this shows that prior policies have a profound influence on the breadth of alternatives that are considered in the SEA.

[21] See Kusters et al., 2024, https://doi.org/10.1016/j.envsci.2024.103920.

5.3| Resolving spatial conflicts

Developing new offshore energy technologies in an already busy offshore area involves dealing with other marine activities, such as fishing, shipping, nature protection and many others. Hence, understanding how to resolve spatial conflicts with existing activities is crucial to minimize delays, ensure investment security, and enable an efficient and sustainable use of shared marine spaces for these technologies.

Based on a case study of spatial conflict resolution practices within MSP in England, Denmark, and the Netherlands, three broad strategies to deal with spatial conflicts can be distinguished. The first is the spatial reservation to relocate conflicting uses. The second is the multi-use of ocean space to minimize spatial conflicts. The third is adopting an ecosystem-based approach to minimize the conflict with nature or mitigate the effects of these spatial conflicts. Where these strategies are determined in national marine spatial plans, more specific guidance is offered through their translation into permitting procedures. Figure 12 contains examples of measures adopted within permitting procedures for offshore wind energy.

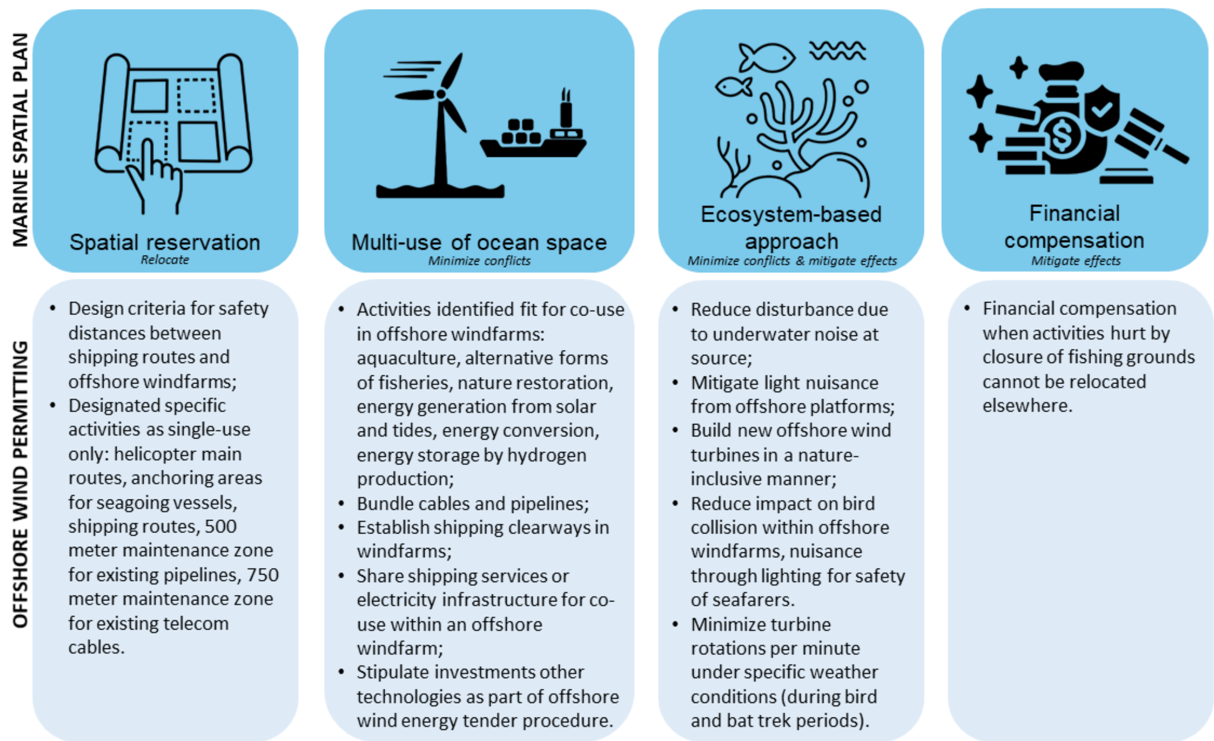


Figure 12 - Overview of conflict resolution measures adopted in the Dutch marine spatial plan and offshore wind energy permitting procedures.

The Dutch approach to resolving spatial conflicts in the marine environment is concentrated in project-specific minimization and mitigation measures adopted as part of permitting procedures. Within these adopted measures, developing offshore wind energy and protecting the marine environment remains the (political) priority. In line with the findings presented in Chapters 5.1 and 5.2, this can be explained by the large ambitions for offshore wind energy towards 2030 and 2050 as well as the legal protection of particular species and habitats under EU Directives and national legislation. Consequently, the freedom to maneuver for policy- and decision-makers in addressing spatial conflicts outside of these measures is limited on a national level.

Overall, these findings suggest that the Dutch approach to conflict resolution is limited by the sentiment to 'administer their way out of the spatial conflicts' on a case-by-case, project-by-project basis. This stands in the way of a more strategic approach involving more long-term, anticipatory decision-making about conflicting spatial claims and trade-offs. This could for instance include proactive relocation measures or compensation for activities hurt by the large-scale roll-out of offshore wind energy. Seeing that spatial pressures will only rise in the coming decades, it is critical that such more strategic considerations will be given a place in future marine spatial planning and permitting procedures.

The limited strategic capacity of Dutch marine spatial planning processes and permitting procedures also holds important implications for the cross-border coordination of energy infrastructure developments. Particularly given the finding that investment into the expansion of the offshore electricity grid across borders is a no-regret option towards 2030 and 2040 (see Chapter 3), coordinating spatial claims and potential conflicts across borders is crucial.

Currently, transboundary cooperation occurs primarily through bilateral consultations on (the environmental effects of) national marine spatial plans based on the Espoo Convention.[22] Existing transboundary organizations or platforms[23] for collaboration either lack a cross-sectoral perspective enabling an integrated balancing of trade-offs, the (political) mandate for shared decision-making, or are temporary and experimental projects without much policy impact. However, unlocking sufficient physical space to accommodate the roll-out of a more integrated offshore energy system requires greater collaborative efforts and shared policy frameworks.[24] The Greater North Sea Basin Initiative provides a promising way forward, aiming to "provide a regional platform for spatial integration of all uses by making proposals for better aligning maritime spatial planning and effective management processes, efficient management processes and coordinating sectoral interests across boundaries."[25] Research is still being conducted into how this new initiative may enable a strategic balancing of conflicting spatial claims across borders and how it supports the development of a more integrated offshore energy system.

[22] United Nations Convention on Environmental Impact Assessment in a Transboundary Context, 1991,

[23] Such as the North Seas Energy Cooperation, the North Sea Regin Maritime Spatial Planning Collaboration Group, the OSPAR Commission, the International Council for the Exploration of the Seas, and the North Sea Advisory Council.

[24] See Guşatu et al., 2020, https://doi.org/10.3390/ijgi9020096

[25] As stated by the Ministerial Conclusions establishing the Greater North Sea Basin Initiative in November 2023,

6| Legal challenges for innovative offshore energy technologies

The feasibility of developing innovative offshore energy technologies needs to be assessed from a legal perspective. While technology usually requires the law to keep up with rapidly changing trends, offshore energy technologies are developing at a pace that the law simply cannot keep up with. Research in the DOSTA project identified several legal uncertainties and barriers to the development of alternative cable connections, electricity storage and hydrogen production and transport infrastructure in the Dutch North Sea.

Without legal certainty, investments will not be made, and new developments will come to a halt. Securing funding can be particularly difficult in situations where there is no legislation for a particular energy technology, where laws and regulations only partially apply to the technology, or where there are conflicting provisions. As a result, proactive measures must be taken to address any legal uncertainties and barriers that may impede progress. Ultimately, this increases pressure on policymakers to create a legal framework that reduces uncertainty and thus creates a more favorable environment for investment in emerging offshore renewable energy technologies. Legal solutions can include a variety of measures, such as amending existing laws or developing new ones.

The following sections outline the legal barriers to the three innovative offshore energy technologies identified in the DOSTA project and propose possible legal solutions to overcome these barriers.

6.1| Alternative offshore cable connections

In the case of alternative offshore cable connections, existing EU and Dutch electricity law sets out basic principles and concepts relevant to their operation but lacks specific provisions enabling their development. In the following, the identified legal challenges and viable solutions are discussed separately for (1) multi-purpose interconnectors and (2) generator-to-user and grid-to-user cables.

Multi-purpose offshore interconnectors

The concept of multi-purpose offshore interconnectors is recognized in EU law. However, their development faces legal challenges, in particular the requirement for TSOs to make at least 70% of the interconnection capacity available to the market. As the capacity of multi-purpose interconnectors must be shared between the connected offshore wind farms and other market participants, compliance with this 70% rule is complex. It essentially requires that 70% of the capacity be available for cross-zonal flows, leaving only 30% for the connected wind farms. Three legal solutions have been proposed to address this issue:[26]

[26] For an elaborate overview of the three approaches to address the legal challenges hindering the development of multi-purpose offshore interconnectors, see Nieuwenhout, Regulating Offshore Electricity Infrastructure in the North Sea: Towards a New Legal Framework (PhD thesis at the University of Groningen, 2020), p. 77–90.

1. Classify multi-purpose interconnectors as conventional interconnectors under EU electricity law. However, this could undermine their economic and legal viability. Exemptions from capacity allocation could be requested, as seen in the KFCGS project between Denmark and Germany, though this approach lacks long-term stability.
2. Create a new asset category for these interconnectors, supported by rules that consider their dual functionality. This would ensure access for connected wind farms to the market and provide compensation for curtailment due to capacity constraints. Although updating the legal framework is time-consuming, it is timely given the ongoing development of a new electricity market design in the EU.
3. Establish offshore bidding zones, which would bypass the 70% capacity rule as the cables would be classified as cross-zonal interconnection cables and 100% of the cable capacity would be available for cross-zonal trade, allowing full utilization of the interconnectors. However, this requires significant market restructuring, which could have a negative impact on the revenues of offshore wind farm developers, while disproportionately benefiting TSOs. This could be partially offset by the redistribution of congestion revenues.

Simultaneously pursuing a new asset category and offshore bidding zones could provide the highest legal certainty. Similar challenges for the multi-purpose interconnector between the Netherlands and the UK may necessitate analogous solutions. However, the EU-UK Trade and Cooperation Agreement, which governs conventional interconnectors, does not fully accommodate these options. Specific provisions should be introduced to address the dual functionality of these interconnectors, with some issues potentially resolved through bilateral agreements between the concerned states, given that these interconnectors fall outside the EU Electricity Regulation.

Offshore generator-to-user and grid-to-user cables

The legal challenges identified for generator-to-user and grid-to-user cables revolve around three key issues. The first issue concerns the legal permissibility of establishing alternative offshore cable connections. Under the Electricity Act, it is not legally permissible to connect offshore electricity generators or users other than offshore wind farms to the offshore network developed and operated by TenneT. In addition, there is uncertainty about the permissibility of a cable connection between an existing or new offshore wind farm connected (or to be connected) to the offshore network and an offshore electricity user, such as a storage, conversion, or hydrocarbon installation. This scenario would require the facilitation of a joint offshore network connection, commonly referred to as cable pooling. In essence, this means that an offshore storage, conversion or hydrocarbon installation is connected to the offshore network via the network connection point established for the offshore wind farm. Although recent amendments to the Wind Energy at Sea Act now allow for a cable connection between a new offshore wind farm and an offshore installation, these amendments do not facilitate offshore cable pooling. In addition, if the Energy Bill is passed, an offshore end user of electricity will be able to establish a separate connection to the offshore electricity network.

A second issue is the legal classification of the cables concerned and the third is the legal framework that applies to them. While the EU Electricity Directive defines (classifies) different categories of electricity cables and networks and thus the rules applicable to their development and operation, it does not fully address the specific characteristics of these types of cables. Although they could be classified as direct lines and be subject to the rules applicable to such lines, the current rules for direct lines in the Electricity Act and the Energy Bill need to be extended to the offshore area. The EU could play a more proactive role in these alternative offshore cable connections by establishing specific rules for their development and operation, especially given the cross-border nature of these cables. To address the legal challenges identified above, amendments to the Dutch Wind Energy at Sea Act and the Energy Bill are essential to provide legal certainty. Such amendments should, where technically feasible, provide for separate connection rights to the offshore network for both electricity users and storage operators, and allow for offshore cable pooling for offshore electricity generation, storage, conversion, and hydrocarbon installations. They should also provide clarity on the classification of the cables concerned and who should develop and operate such cables.

6.2| Electricity storage

Currently, no specific EU or national policy for the development of *offshore* electricity storage exists. A review of the existing EU and Dutch legal frameworks reveals both general and offshore-specific legal barriers. General barriers include uncertainties about the definition, classification, ownership, and operation of energy storage within the electricity system, while offshore-specific barriers include uncertainties in the permitting procedure for the development of standalone storage facilities and those co-located with offshore wind farms. Several legal solutions have been proposed to address these barriers. First, the Netherlands should formally adopt the Energy Bill, which incorporates the framework for energy storage from the EU Electricity Directive. This bill should then be amended to extend its provisions to storage in the EEZ, thereby increasing legal certainty regarding offshore ownership, operation, and network access.

The current permitting regime for the development of electricity storage in the Dutch EEZ under the Environment and Planning Act is general, non-competitive, and operates on a 'first come, first served' basis. While this framework provides legal certainty, a specific and competitive permitting regime–like what the Wind Energy at Sea Act stipulates for offshore wind farms–is more effective. A specific permitting regime could be introduced in either the

Wind Energy at Sea Act or the Energy Bill. For storage co-located within offshore wind farms, the conditions should be aligned with those imposed on the offshore wind farm developer, possibly by incorporating them into the Wind Energy at Sea Act. This would ensure consistency, particularly regarding environmental impact assessments, safety distances and operational responsibilities.

If standalone storage is regulated separately under the Energy Bill, clear rules should define when storage is considered co-located. This could be done by adopting the Renewable Energy Directive definition of such facilities, as integrated with renewable generation, and connected to the network via the same connection point (see above). To further reduce ambiguity in the permitting regime, it is recommended that tendering procedures for storage facilities be introduced. Storage could either be included in existing wind farm tenders or be subject to a separate tendering process. In either case, such procedures should be included in existing or new legislation, following the example of the Wind Energy at Sea Act.

6.3| Hydrogen production and transport infrastructure

The EU legislator has applied the current gas market regime to the hydrogen sector, subjecting hydrogen networks to unbundling and regulated Third Party Access (TPA) rules. This decision is in line with the potential for hydrogen transport over the existing natural gas network and the repurposing of gas infrastructure for hydrogen. However, as the hydrogen market is still developing, exemptions may be necessary. The recast Gas Directive allows for exemptions from unbundling for hydrogen networks established before its adoption or in specific areas, and exempts hydrogen networks from regulated TPA until 2033. While these exemptions are intended to encourage investment, further adjustments may be necessary if the hydrogen market does not develop as expected. In addition, the recast Gas Directive distinguishes between methane-based and hydrogen-based infrastructure, which raises the need to clarify when a natural gas network transitions to a hydrogen network and becomes subject to different rules.

To bring natural gas and hydrogen regulations under one framework, the new EU hydrogen legislation will need to be transposed into national law, preferably through the Energy Bill. This approach would reflect the EU strategy and streamline the legislative process. While many aspects of the operation of hydrogen networks will be clarified once the recast Gas Directive has been transposed into Dutch law, the Dutch legislator still needs to clarify the permissible hydrogen content in existing natural gas networks and officially designate an operator for hydrogen transmission networks. In case Gasunie is designated to operate hydrogen transmission networks (which is possible under the unbundling regime in the recast Gas Directive), it will have to do so through a separate entity and additional safeguards against cross-subsidies will be required.

Offshore hydrogen transport presents unique challenges, requiring tailored legal solutions. The EU regime does not distinguish between upstream and downstream hydrogen pipelines, complicating the repurposing of upstream natural gas pipelines for hydrogen transport.[27] The Dutch legislator thus needs to clarify the integration of repurposed pipelines into the offshore hydrogen network and how ownership and operation of these pipelines will be transferred to the hydrogen transmission network operator. This involves defining compensation schemes and conditions for such transfers, especially when both economic ownership and operation are transferred to Gasunie.

Clear guidelines are also needed for offshore hydrogen production, whether the electrolyzer is developed on existing (or disused) hydrocarbon installations, new installations, artificial islands or within offshore wind turbines. At present, offshore energy activities can be authorized under sector-specific legislation, such as the Mining Act or the Wind Energy at Sea Act, or under the broader Environment and Planning Act. However, while sector-specific legislation does not cover offshore hydrogen development, the Environment and Planning Act is general in scope and not tailored to the specific characteristics of offshore electrolyzers. Introducing a permitting regime and competitive tendering process–like that proposed above for offshore electricity storage (Section 6.2)–could improve legal certainty. In addition, specific operating, and safety regulations, like those for offshore hydrocarbon production, should be introduced to address the risks associated with offshore hydrogen production.

The (re-)use of offshore hydrocarbon installations for hydrogen production introduces additional complexity. Recent amendments to the Mining Act allow reuse of these installations for other activities but do not specify the necessary conditions required for such reuse. They also do not address the issue of simultaneous use of such installations. For both to be possible, agreements need to be made between hydrocarbon license holders and hydrogen permit holders for either shared use or transfer of these installations. The Mining Act should be amended to facilitate simultaneous use, clarify responsibilities, and define conditions for (re-)use, including financial arrangements and safety requirements.

[27] An upstream pipeline network is defined as "any pipeline or network of pipelines operated or constructed as part of an oil or natural gas production project, or used to convey natural gas from one or more such projects to a processing plant or terminal or final coastal landing terminal", see Article 2(16) of the recast EU Gas Directive.

7| Policy and legislative recommendations

Based on the findings of the DOSTA project, we present targeted recommendations for policymakers and decision-makers involved in the offshore energy system. We outline six key recommendations designed to accelerate the adoption of innovative offshore energy technologies, supporting the large-scale expansion of offshore wind energy in the Dutch North Sea. These recommendations are organized according to their relevance on the short-, medium-, and long-term.

1. **Embed alternative cable connections, offshore energy storage and power-to-hydrogen applications in the forthcoming North Sea Energy Infrastructure Plan**

To explore what infrastructure is needed to facilitate the growth of offshore wind energy after 2030, the Dutch government is currently drawing up the North Sea Energy Infrastructure Plan (*Energie Infrastructuur Plan Noordzee*, EIPN). The government already promises the EIPN to cover offshore hydrogen production and reuse of existing gas infrastructure for transport, as well as its integration with electricity infrastructure on the Dutch mainland and surrounding North Sea countries.[28] It also is foreseen to provide ideas on the decision-making process on offshore energy infrastructure when it comes to the division of roles, market organization (rules, laws, and conditions for operating in this sector), government legal instruments. The emergent development of this long-term vision on North Sea energy infrastructure can already provide developers with the (legal and economic) certainty required to justify investment decisions and continue project development.

The DOSTA project emphasizes that *more clarity* is needed on the role of alternative cable connections and offshore energy storage in the future offshore energy system. As such, we specifically recommend the EIPN to cover the following elements:

- The potential roll-out of multi-purpose interconnectors to connect wind farms across borders and foreseen connecting countries or hubs.
- Additional clarity on the regulation of generator-to-consumer cables and grid-to-user cables to facilitate a potential implementation of offshore energy storage systems.
- A potential streamlining of permitting processes for co-location of activities within offshore wind farms, particularly regarding energy storage facilities.
- Safety guidelines for new offshore activities and identifying competent authorities for oversight.

[28] See https://english.rvo.nl/topics/offshore-wind-energy/infrastructure-sea#north-sea-energy-infrastructure-plan

2. **Invest in an expansion of the offshore electricity grid, notably cross-border connections**

The results indicate that investing in an expansion of the offshore electricity grid is, economically speaking, a no-regret option. Specifically, new offshore connections between Norway and other North Sea countries are found to support significant cost and emission reductions, leveraging Norway's hydro resources. Ultimately, investing in electricity grid expansion may also downplay the demand for energy storage and hydrogen production capacities, potentially resulting in greater cost savings.

To expand the offshore electricity grid, various legal barriers need to be addressed. First, the current EU framework covers interconnectors and some hybrid cables, but not all alternative cable types. It is recommended that the EU create separate asset categories for offshore generator-to-user and offshore grid-to-user cables and establish specific rules for their development and operation, especially as such cables may also be developed across national borders.

This sea basin perspective also requires greater international alignment and decision-making (also see Recommendation 6). Namely, although the total system costs may decrease, the distribution of costs and benefits will change and instigate international dependence. For example, where Norway's costs will rise, countries such as the United Kingdom and the Netherlands may benefit greatly. Hence, just remuneration mechanisms in line with energy justice considerations must follow investments in a more interconnected offshore electricity grid for countries such as Norway to commit to such ambitions.

3. **Adapt EU and national energy laws to include provisions for emerging technologies and ensure their applicability within the Exclusive Economic Zone**

It is important to ensure that the Energy Bill includes provisions for innovative offshore energy technologies such as alternative cable connections, electricity storage, electrolyzers and hydrogen pipelines. This will require the rapid and effective transposition of the recast EU Electricity and Gas Directives into the Energy Bill. It is equally important to extend these provisions to developments within the Dutch EEZ. At present, the forthcoming Energy Bill, like the current Electricity and Gas Acts, has limited applicability in the EEZ. As the offshore energy system expands to include not only producers but also storage operators and consumers, the Energy Bill will need to adapt. Specific considerations that are unique to the offshore energy system, such as technical limitations in connecting offshore storage, conversion or hydrocarbon installations to offshore substations or offshore wind farms, and spatial considerations for integrating storage and conversion installations with offshore wind farms, need to be addressed in the law.

4. **Strengthen cross-sectoral coordination in marine spatial plans and regulatory frameworks**

Current Dutch planning processes and legislation are sector-oriented and face challenges in adapting to innovative technologies and integration requirements. For instance, although the Program North Sea 2022-2027 concerns the overall management of the Dutch North Sea, its tunnel vision on enabling offshore wind energy developments hinders a strategic balancing of offshore wind with other marine activities. The fragmented approach to offshore energy legislation makes cross-sectoral alignment even more difficult, particularly regarding the reuse of offshore hydrocarbon infrastructure for hydrogen.

Strengthening cross-sectoral coordination in marine spatial plans and corresponding processes can be done by:

- Introducing novel technologies in updates of the Program North Sea and related policies
- Providing concrete guidance in offshore wind energy tenders and corresponding permitting procedures on how to combine elements enhancing system integration
- Including more far-reaching spatial choices to (proactively) address existing and expected spatial conflicts, for example, through proactive relocation of conflicting activities, buy-outs, or combined tender procedures.
- Exploring alternative options to meeting policy goals by assessing different spatial configurations within Strategic Environmental Assessment (also in pursuit of Recommendation 5).

The cross-sectoral perspective in regulatory frameworks could be strengthened by adopting an integrated approach to the regulation of offshore energy activities, treating all offshore installations and networks holistically. This would reduce legal uncertainty, improve clarity, and streamline governance by addressing cross-cutting issues and accommodating emerging technologies. The progress made in the Energy Bill towards merging the Electricity and Gas Acts is a step in this direction. There is also a need to align the provisions on offshore energy activities in the forthcoming Energy Bill with the regulation of offshore wind farms under the Wind Energy at Sea Act and offshore hydrocarbon activities under the Mining Act. To avoid a fragmented regulatory approach, consideration should be given to integrating aspects of these sector-specific laws into the Energy Bill. This would also require alignment with the Environment and Planning Act, which currently governs the planning and permitting process for offshore energy activities not covered by sector-specific legislation. Alternatively, the relevant provisions from the Energy Bill, the Wind Energy at Sea Act, the Mining Act and the Environment and Planning Act could be consolidated into one comprehensive law for offshore energy activities.

5. **Strengthen the role of environmental considerations in MSP processes**

Given national and international commitments to marine environmental protection, the environmental status of the marine environment has become a crucial element in decision-making on new infrastructure developments offshore. In particular, the 2022 Kunming-Montreal Global Biodiversity Framework aspires at least 30% of marine areas to be protected[29]. Also, the Program North Sea 2022-2027 recognizes a nature transition, stating that all uses must fit within the ecological carrying capacity of the North Sea.

Although policy instruments such as Strategic Environmental Assessments and Environmental Impact Assessments are in place and benefit from a strong legal basis, the role of environmental considerations in policy making processes is limited. Strategic Environmental Assessments can support MSP processes under certain conditions. First, sufficient freedom to change course during policy formulation is key. Although any spatial planning exercise is complex, initiating the SEA at an early stage of the planning process enables the outcomes of the assessment to have the most possible impact in decision-making. Second, more structural collaboration between science, industry and policymakers is essential to share available data and understanding, most notably on ecological information. Specifically, this requires investments into the so-called science-policy interface, including creating a basis for knowledge co-production and uptake in strategic decision-making.

6. **Facilitate and intensify transboundary collaboration to enable cross-border offshore energy developments.**

Innovative offshore energy technologies, particularly alternative offshore cables, have cross-border implications that may require more than national action. First, a harmonization of offshore wind and electricity network rules in the North Sea countries could increase efficiency by streamlining planning and authorization procedures. It could also reduce administrative costs and improve cooperation on cross-border projects, including hydrogen initiatives. A new EU mandate on gas quality standards, including hydrogen content, may also be needed to avoid restrictions on cross-border gas flows.

Most of all, a more structured and permanent approach to transboundary cooperation is currently missing on the North Sea. Although the Esbjerg and Ostend Declarations emphasize the need for intensified collaboration, they are not legally binding, and do not specify on what grounds and how to collaborate. The forthcoming Greater North Sea Basin Initiative shows a promising way forward, though it remains unclear how its governance and subsequent policy impact will take shape. On the long-term, the GNSBI will provide a platform for collaboration

[29] See Target 3 of the framework, https://www.cbd.int/gbf/targets/3.

with a shared governance framework and capacity to act strategically beyond borders. This is a key condition for developing a truly integrated offshore energy system towards 2050.

In the meantime, transboundary collaboration should focus on:

- Aligning conflict resolution strategies across borders
- Exploring the possibility for an integrated electricity grid in which Norway plays a significant role
- Sharing knowledge and data, notably ecological data, to provide a shared basis for marine spatial plans
- Considering under what conditions the collaboration between EU and non-EU member states on the North Sea region can materialize
- Discuss whether and how transboundary collaboration may also involve shared spatial planning efforts, e.g., in the case of designating wind farm areas across borders

7. Continue to stimulate interdisciplinary research to facilitate the development of an integrated offshore energy system.

Above all, the DOSTA project has shown the value of interdisciplinary research into the development of the larger offshore energy system. It is not only the technical and economic feasibility shaping how the offshore energy system of the future will look like (Chapter 3 and 4), but also the broader legal and governance regimes. Combining these insights provides novel and important considerations for policy- and decision-makers. However, large uncertainties and knowledge gaps remain. Hence, future research funding calls should reward interdisciplinary approaches, as only this will provide a complete yet nuanced understanding of developing offshore energy systems.

8| Further reading

The following academic work was published in the context of the DOSTA project by the involved researchers:

- Andreasson, L.M. (2021). 'The Regulatory Framework for Green Hydrogen Developments in the North Sea' in M.M. Roggenkamp, C. Banet (eds), *European Energy Law Report* (Intersentia). https://doi.org/10.1017/9781839702211.016
- Andreasson, L.M. (2024). 'Offshore Production and Transport of Green Hydrogen: A Case Study on Denmark and the Netherlands' in R. Fleming (ed), *The Cambridge Handbook of Hydrogen and the Law* (Cambridge University Press). Forthcoming.
- Andreasson, L.M. (2025). 'Energy Transition in the North Sea: The Legal Framework for Innovative Energy Technologies in the EU and the Netherlands' (PhD Dissertation). Forthcoming.
- Kusters, J.E.H., Van Kann, F.M.G., & Zuidema, C. (2023). Exploring agenda-setting of offshore energy innovations: Niche-regime interactions in Dutch Marine Spatial Planning processes. Environmental Innovation and Societal Transitions, 47, 100705. https://doi.org/10.1016/j.eist.2023.100705.
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- Ossentjuk, I., Wiegner, J., Nienhuis, R., Griffioen, J., Vakis, A., & Gazzani, M. (2024). The techno-environmental potential of offshore pumped hydro storage: A case study of the Dutch North Sea. EGU24. https://doi.org/10.5194/EGUSPHERE-EGU24-12276.
- Wiegner, J.F., Ossentjuk, I. M., Nienhuis, R.M., Vakis, A. I., Gibescu, M., & Gazzani, M. (2024). Harvesting the Wind - Assessment of Offshore Electricity Storage Systems. 53, 2185–2190. https://doi.org/10.1016/B978-0-443-28824-1.50365-3.
- Wiegner, J.F., Andreasson, L.M., Kusters, J.E.H., & Nienhuis, R. M. (2024). Interdisciplinary perspectives on offshore energy system integration in the North Sea: A systematic literature review. Renewable and Sustainable Energy Reviews, 189, 113970. https://doi.org/10.1016/J.RSER.2023.113970.
- Nienhuis, R.M., van Rooij, M., Prins, W.A., Jayawardhana, B., & Vakis, A.I. (2023). Investigating the efficiency of a novel offshore pumped hydro energy storage system: Experimental study on a scale prototype. Journal of Energy Storage, 74, 109374. https://doi.org/10.1016/j.est.2023.109374.

Unpublished work:

- Kusters, J.E.H., Van Kann, F.M.G., & Zuidema, C. (2024). Spatial conflict resolution in Marine Spatial Plans and permitting procedures: an analysis of measures adopted in Denmark, England, and the Netherlands. Frontiers in Marine Science. *Submitted*.
- Wiegner, J.F., Tiggeloven, J.L., Bertoni, L., Ossentjuk, I.M., & Gazzani, M. (2024). AdOpT-NET0: A technology-focused Python package for the optimization of multi-energy systems. Journal of Open Source Software. *Submitted.*
- Wiegner, J.F., Gibescu, M., & Gazzani, M. Unleashing the full potential of the North Sea - Identifying key energy infrastructure for 2030 and 2040. *Forthcoming*.