North Sea Energy
offshore system integration

D6.3

North Sea Energy 2023-2025

Logistics

Navigating the North Sea transition!

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

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

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

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

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

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

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

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

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Prepared by:

TNO
Vadim Uritsky
Janaki Mohanan Nair

Checked by:

TNO
Vinit Dighe
Joris Koornneef

Approved by:

TNO
Madelaine Halter

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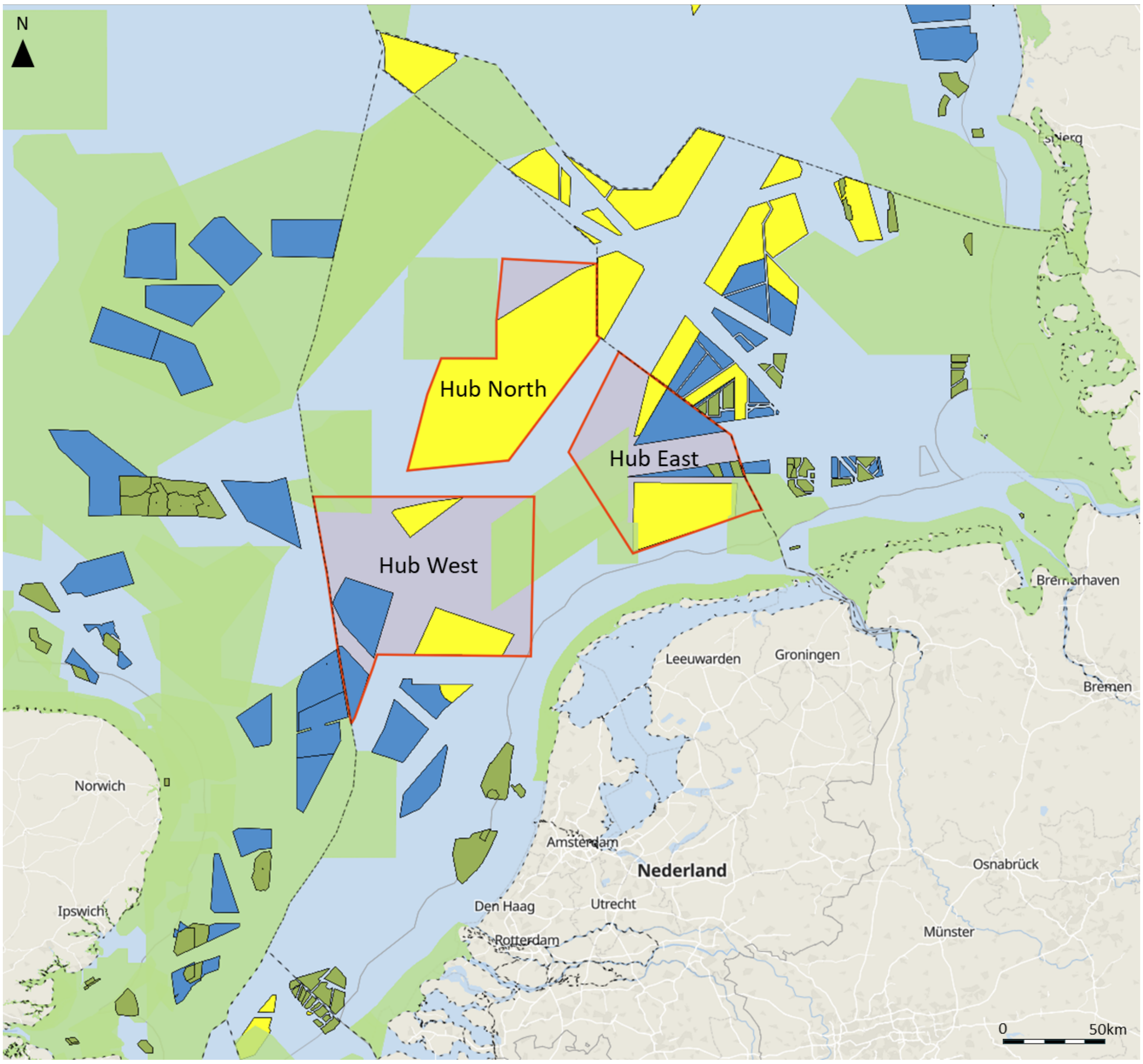
Executive summary

In this study, analyses of the logistics of performing Operation and Maintenance (O&M) activities in the North Sea were conducted and analysed. Given hub blueprints input from WP1, key technologies with the potential of upcoming implementation were identified for each of Hub West, East, and North, and used to define representative scenarios.

For Hub West, the logistics requirements of wind farm technology, floating solar PV farms, and repurposed platforms for CO_2 storage (Carbon Capture and Storage - CCS) activities were outlined, with a corresponding baseline scenario defined wherein the required O&M activities would be performed independently using separate pools of resources. Further scenarios were defined wherein logistics were synergized by using common pools of resources, where possible. Long-term simulations of these scenarios were run using the UWiSE O&M Planner tool to quantify and analyse the differences in key O&M metrics such as wind farm/solar farm availabilities, vessel and labour costs, distances travelled, and atmospheric emissions. It was found that while the effect of sharing resources with a solar PV farm led to a 3-4% drop in wind farm availability, the required number of technicians dropped by up to 34% and yearly vessel costs reduced by up to €16.5 million for a 2 GW wind farm scenario. Vessel distances also reduced by up to 30%, significantly cutting emissions of CO_2, NOx, SO_2 , and $PM_{2.5}$.

For Hub East, the logistics requirements of wind farm technology were outlined along with the O&M requirements of the upcoming 500 MW DEMO2 electrolysis system, as well as a possible natural gas exploration platform in the N5 area. A similar procedure was performed as with Hub West, where a baseline scenario was simulated where O&M was conducted independently between assets, along with a scenario where O&M was synergized. A similar analysis was conducted, where it was found that synergizing O&M led to a 2% reduction in wind farm availability, primarily due to the large travel distances required, but also a reduction in distance travelled by up to 50%, with similarly large emission reductions. Although large benefits from technician synergies were not found, due largely to the difference in skill sets required for the different types of O&M, vessel synergies led to a yearly reduction of €4.6 million for the 700MW wind farm scenario.

For Hub North, the logistics requirements of wind farm and electrolysis systems were outlined for two scenarios where the configuration in which the electrolysis production varied. The first scenario was one in which a 4 GW wind farm produces power, part of which is converted to hydrogen using 2 GW of electrolysis equipment located centrally on a series of platforms. The second scenario was one in which the corresponding wind turbines were equipped with electrolysis equipment, at a ratio of 15 MW wind to 12 MW electrolysis capacity, to produce and export hydrogen directly. These scenarios were simulated for a long-term duration as well, and it was found that the de-centralization of the electrolysis equipment led to significantly lower availabilities and increased vessel costs, but lower technician costs. It was found that these results depended heavily on the maintenance requirements of electrolyser systems and could significantly improve as electrolyser maintenance becomes more optimized.



Geographic map of the Dutch sector (mainly) of the North Sea with the outlines of the three hubs of NSE (red polygons), in context with operational windfarms (dark green), planned windfarm areas (dark blue), search areas for developing windfarms (yellow), and nature areas (light green).

1 Introduction

1.1 Background

Offshore logistics play a pivotal role in the successful development, operation, and integration of complex systems in the North Sea. As energy demands evolve and the industry moves toward more integrated solutions that encompass oil and gas, wind, and emerging technologies such as carbon capture and storage (CCS), efficient logistics have become increasingly critical. The North Sea presents a challenging environment characterized by harsh weather conditions, remote locations, and a dense network of existing infrastructure. These factors demand a robust and highly coordinated logistics framework to support system integration activities, including the transportation of equipment, personnel, and supplies, as well as the installation and maintenance of offshore platforms, pipelines, and renewable assets.

As the future North Sea Energy system grows, offshore logistics are becoming more and more important to maintain proper operation of these systems. Logistics ensures that assets are inspected on time to prevent failure, that key supplies are delivered when needed, and that, in case of failure, replacement parts and technicians can get to offshore structures as soon as possible. As such, logistics forms the backbone of the North Sea Energy system. Making sure that the logistics system can grow alongside the North Sea energy infrastructure in a cost-effective manner while simultaneously minimizing the negative environmental effects of emissions and the impact of increased vessel usage on the ecology of the North Sea will require an effective and optimized logistics strategy. In this part of WP6 of the NSE5 programme, the groundworks will be laid for the development of methods for such an optimization process.

The report on the logistics work done in the NSE4 programme contained a comprehensive overview on the background of offshore logistics and logistics sharing in the North Sea area, most of which is still relevant for this work. For brevity's sake, and to not repeat the same work twice, this background will be left out of this report. The interested reader can freely access and read the NSE4 report [1] on the programme's website[1].

1.2 Research focus

Within the NSE4 programme, offshore logistics was already investigated in detail from the perspective of shared logistics between the wind and oil & gas sectors. There, the case studies that were worked out were relatively generic in order to provide general results that could be applicable to different situations. In this work, the research will further build upon the work done in NSE4, but with the aim of specifying more towards the expected design of the future North Sea energy system. This is done based on the outcomes of WP1 of the NSE5 programme, in which spatial blueprints are created for the three North Sea Energy Hubs (West, East, and North). These blueprints contain the expected locations and installed capacities for various technologies key in the energy transition, including oil & gas platforms,

[1] (https://north-sea-energy.eu/en/results-2022/).

offshore CO_2-storage installations, offshore hydrogen, wind energy, and floating solar power, and will be used to define the inputs and boundary condition to the logistics analyses done in this WP.

In addition, while the work done in the previous NSE programme mainly focussed on the wind and oil & gas sectors, this work will look into more detail into additional technologies such as CO_2 storage, offshore electrolysis, and floating solar. In this, the blueprints from WP1 will be guiding in determining whether these technologies need to be included in the logistics planning done in this work (e.g. some hubs might not include one or more of these technologies, and thus they will also not be included in the logistics scenarios). Since many of these technologies are currently not in use yet (or only in very early research stages), one of the key challenges of this work is identifying their logistic (maintenance) needs and dealing with the associated uncertainties reliably during the analyses.

1.3 Research questions

To guide the activities in this sub-WP, two main research questions were formulated:

1 What might a synergized offshore strategy of the future look like?
2 How can we develop a process for optimizing the logistics strategy for a large offshore energy system?

The next chapter of this report focuses on the activities required to be completed and the methods to be used to answer these two main questions.

2 Methodology

2.1 Research activities

Based on the research questions defined in the previous chapter, the following activities have been foreseen:

1 **Identifying logistic requirements and constraints.** The first phase of the work will focus on listing which activities are planned to take place in the different hubs, and which physical assets are involved in these activities. For these assets, as far as the information is available, the type and frequency of different (operation and maintenance) logistic activities are identified, which can then be incorporated into the optimization methods. In NSE4 many of these activities have already been identified for the wind and oil and gas sectors. NSE5 will aim to do the same for technologies such as offshore electrolysis and CO2 storage requirements. In addition, the requirements for different vessel types per activity will also be identified, as this largely determines how activities could be shared and in which way the logistic fleet can be optimized for a given maintenance campaign. This activity will also establish which offshore structures (wind farms, platforms, energy islands, etc.) will be included in the optimization process.

2 **Finding potential logistic synergies.** With the logistic needs and constraints identified, potential synergies between activities from different sectors will be investigated such that vessels can be shared between them in order to reduce costs, emissions, and impact on the North Sea ecology. Again, this work will expand upon the results of NSE4.

3 **Defining Key Performance Indicators.** In order to be able to optimize the logistic of a system, the measure by which the optimized scenario is evaluated should first be defined. In this activity, the KPI's used for this will be defined. In particular, NSE5 will aim to include system availabilities, maintenance cost metrics for different resource type (vessels, technicians, etc.), and ecology-important KPIs such as travel distance and emission reductions (similar as in NSE4).

4 **Performing quantitative analyses of Hub West and Hub East.** The potential logistic synergies identified in Step 2 will be explored through UWiSE O&M Planner simulations. A baseline simulation will be defined that represents a status quo, and the impact of logistic synergies will be estimated through comparison with additional simulations, in which these synergies are reflected through modelling changes. Comparisons will be framed in terms of the KPIs that were developed in Step 3.

5 **Performing a quantitative analysis of Hub North.** In this activity, potential O&M strategies will be investigated according to the KPIs defined in Step 3. Potential approaches will be determined according to the possible configurations that energy systems may appear in in Hub North, given the directions outlined in WP1. UWiSE O&M Planner simulations will be used to quantify the differences between the strategies when possible.

6 **Approach for an optimization method/workflow.** Using the results of the analysis, an approach will be developed for a workflow that would be able to produce an optimized logistic strategy for the offshore energy systems in the North Sea. This entails a discussion on what input variables would need to be optimized, what KPIs are valuable to be optimized, the tools that may be used for that optimization, and other relevant aspects. This work does not entail performing the optimization procedure itself, but is intended as a platform to discuss how optimization could be performed in future work.

2.2 Scope

In the initial plan for the logistic activities within NSE5, it was decided to focus the analyses on two out of three Hubs, with one quantitative and one qualitative. However, the plan was later shifted to include quantitative analysis of all three Hubs, with a difference in temporal and technical scope between them.

Based on the outcomes of the WP1 within the first sprint, it was decided that the first quantitative analysis was to be for Hub West. Based on the blueprints of WP1, Hub West was considered to be where the development would occur earliest, with largely established technology such as wind farms and O&G platforms. In the short term, it is expected that development in Hub West, in the context of O&M strategies, would focus on the synergies possible when co-maintaining wind farms and O&G platforms together, similar to the study in NSE4. Later developments in WP1 showed a potential for floating solar PV farms to also be installed in Hub West, which allowed for the novel investigation into co-located wind and solar PV logistics to be analysed.

The next quantitative analysis was decided to be conducted for Hub East, where some offshore hydrogen production is expected to be developed offshore. The analysis therefore entails the possible synergies between wind farm power production and hydrogen conversion with P2G. This is considered further in the timeline, compared to Hub West, so an understanding of the O&M requirements of hydrogen, being less understood, was considered a key research theme in this study. In addition, the potential for additional natural gas development in the N5 area is also considered in this timeframe, the logistic synergies for which will also be included in this analysis.

The final quantitative analysis will be conducted for Hub North, which according to the blueprints of WP1 is expected to be a largely hydrogen-producing North Sea area. Thus, the focus will be on further refining the O&M strategies that could be relevant for large hydrogen-producing energy systems. Because developments are expected to occur furthest along in the timeline, the uncertainty is expected to be highest, meaning that an analysis of different technological configurations was deemed more important at this stage. Thus, an evaluation of key O&M KPIs was performed and compared for different ways in which the hydrogen may be produced.

Regarding the scope of the modelling work to be executed, the following scope, boundary conditions and constraints will be considered:

Technical Scope: Technologies considered will be those defined by WP1.
Temporal Scope: The temporal scope will range from 2030-2050.
Spatial Scope: The spatial scope will comprise Hub West, East, and North.

2.3 Interaction with other work packages

The interaction between this sub-WP and other work packages has been briefly touched upon in previous sections of this report, and are schematically shown in the figure below. The main inputs are expected and have come from WP1, in which the types, scales, and locations of the various activities in the North Sea energy system have been defined per energy Hub. This information is used in this work to define the boundary conditions and inputs for the modelling activities. To shape the direction of the work, input from WP2 Human Capital and WP4.1 Ecology was also taken into account through cross-WP interactions and work packages.

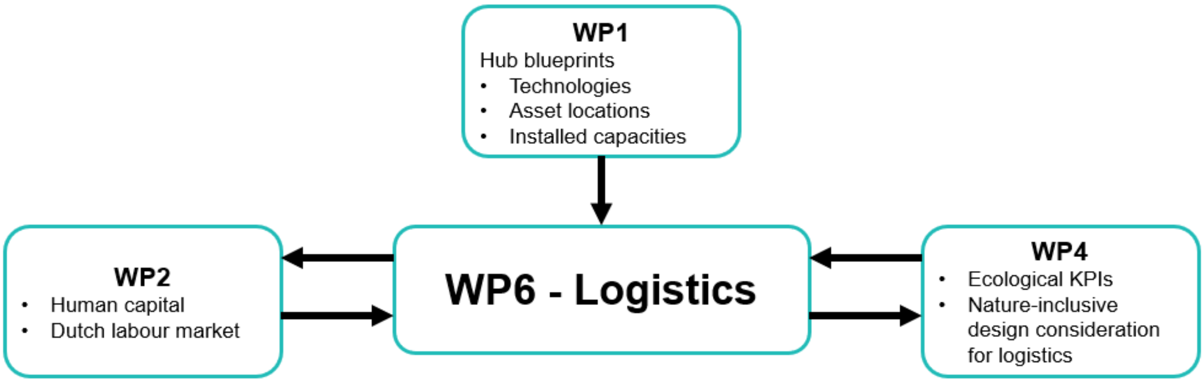


Figure 2-1: Overview of the work package interaction

2.4 Description of the quantitative analyses

The detailed model-based quantitative analysis present in the logistics work package of NSE5 will be mostly conducted through the use of the UWiSE O&M Planner tool, which is a discrete event-based logistic simulator developed by the TNO Wind Energy group. This tool was originally developed a flexible decision-support software for long-term campaign evaluation when conducting operations and maintenance on offshore wind farms. To model the non-wind assets in the current work, additional features were implemented and further extrapolations were done, in order to model assets such as floating solar PV farms, platforms for natural gas production and CCS, offshore electricity storage, and offshore electrolysis.

The software enables users to perform multi-year simulations to calculate O&M costs, wind/solar farm availability and energy production while taking into account uncertainties of weather and wind farm component reliability. Multi-year simulations that consider weather uncertainty by using the Monte Carlo sampling technique provide a valuable framework for decision-making in the planning, design, and operation of offshore wind farms. By running simulations for multiple weather years, the software calculates statistical estimates of the frequency and duration of favourable weather conditions for specific operations. This helps to identify patterns, seasonal variations, and the probability of encountering adverse weather. The software presents the impacts on O&M's key performance indicators of deploying different types and numbers of vessels each with their weather limits of operation. The figure below shows the user interface of UWiSE O&M Planner. This software aims to:

- Assist energy system operators in optimizing O&M choices between various transportation types, equipment, personnel shift and spare part stock management options in terms of standard Key Performance Indicators (KPIs) such as availability and repair costs.
- Conduct scenario analysis for an O&M project by varying the available resources.
- Provide an overview of preventive and corrective maintenance activities, the delays encountered (weather or resource) and associated costs.
- Provide insights into the downtime per component failure mode and per maintenance activities.

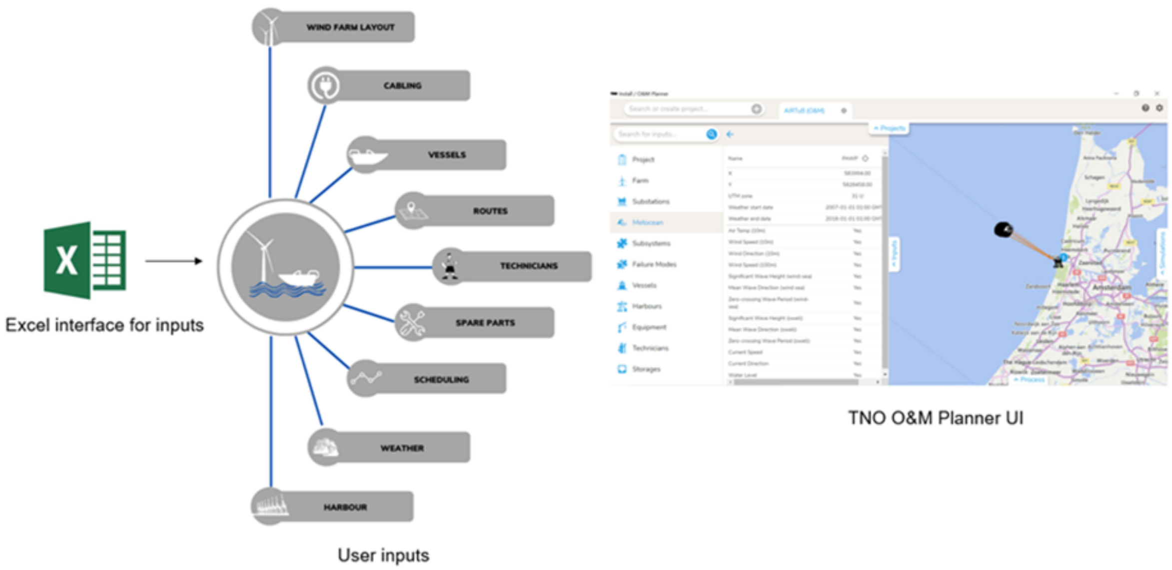


Figure 2-2: Schematic Overview of UWiSE O&M Planner

2.4.1 Logistics requirement inventory

In order to properly model offshore logistic scenarios, information is needed on the logistic requirement for various offshore assets. While this information is available for the wind sector coming from TNO's wind department and to a lesser detailed, but sufficient extent for the oil & gas industry based on data analysis done within NSE4, it is still lacking for many of the newer, less established technologies such as offshore electrolysis, CCS, and floating solar. For this reason, the first activity in this sub-WP was inventorying the logistic/maintenance requirements for these technologies as far as these were known.

For assets where detailed subsystem maintenance requirements were known, maintenance requirements were defined by outlining a list of subsystems, each with relevant failure modes. The stochastic behaviour of each failure mode was described by a set of statistical parameters, as well as the associated maintenance action required to address it. Each maintenance action was then described by a sequential set of operational steps, each with a time duration, weather restrictions, and a set of required resources (vessels, technicians, equipment, etc.). In addition, periodic scheduled maintenance campaigns were outlined, also with fully detailed maintenance actions. The details of these logistic requirements, as they correspond to specific assets, are expanded upon in the corresponding simulation discussion.

3 Hub West – Quantitative Analysis

3.1 Scenario Overview

The quantitative analysis run for Hub West focuses on the logistic synergies that can be obtained, when combining resources to operate and maintain offshore wind farm assets, offshore floating solar PV assets, as well as platforms repurposed for CCS. This work expands on the previous results performed in NSE4, which focused on the logistic synergies found purely between offshore wind and CCS. The following table summarizes the scenarios performed in this analysis.

Table 3-1: Hub West - Scenario Overview

#	Wind Farm Location	CCS Platform Description	Offshore Floating Solar Capacity	Resource Synergy
1	Nederwiek-Noord (NW-N)	No platforms	500.0 MW	None
2				Vessel sharing: wind & solar Technician sharing: wind & solar
3		5 Platforms in the eastern part of the K-block		Vessel sharing: wind, solar, CCS Technician sharing: wind, solar, CCS

For the location of the wind farm, Nederwiek-Noord was chosen for this study due to its proximity to CCS platforms located in the eastern part of the K-block, as well as for its location in Hub West, where floating solar may feature as an energy production asset. A wind farm size of 2.0 GW was chosen, to represent the estimated wind farm sizes in 2030, which led to a wind farm modelled with 133 wind turbines, each with a 15MW rated capacity. The floating solar PV farm was chosen to have a capacity of 500 MW, which was assumed to consist of 50 floater units, each with a rated capacity of 10 MW. The five CCS platforms considered in this study were the same as used in the NSE4 Hub West island simulation, with the same maintenance requirements. The port used in simulations was chosen to be IJmuiden, with the Platform Service Vessel (PSV) assumed to be stationed there as well.

The following figures show the relative locations of the assets chosen for this study, with the asset layouts shown in several levels of detail. The figures on the top show the relative position of the assets in the Dutch part of the North Sea (left), and the layout of the wind farm and CCS platforms in more detail, as well as the location of the floating solar PV farm in the centre of the wind farm. The figure on the bottom shows a close-up of the layout of the floating offshore solar PV farm in more detail. In each of these figures, the circles and squares represent the assets modelled – here the circles are the individual wind turbines, and the squares are the individual floating solar PV modules.

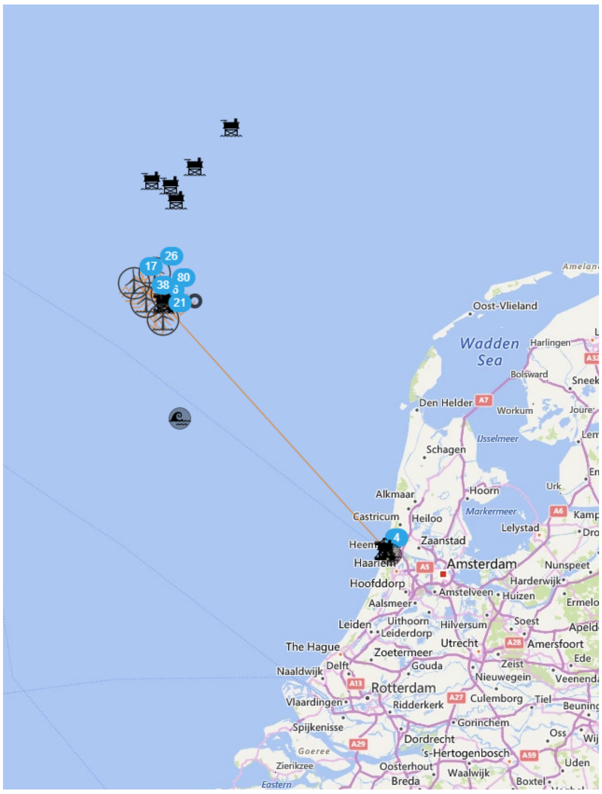


Figure 3-1: Hub West - Graphical Overview (Total system)

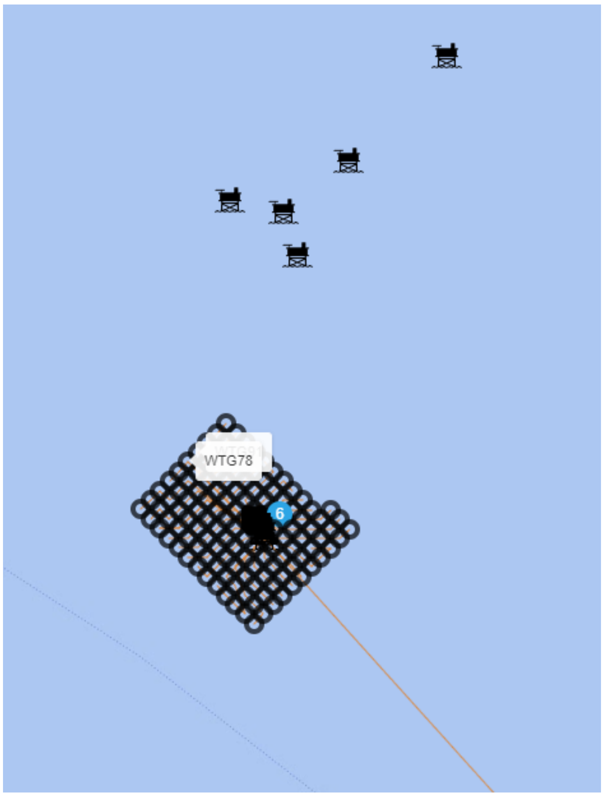


Figure 3-2: Hub West - Graphical Overview (Asset level)

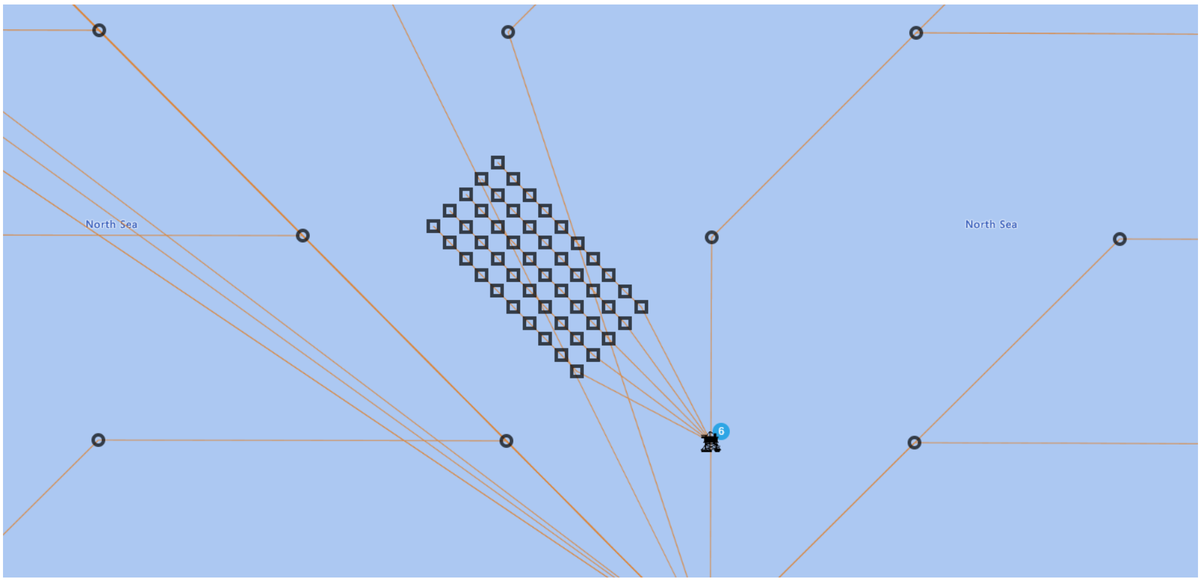


Figure 3-3: Hub West - Graphical Overview (Solar PV farm details)

3.2 Logistics Overview

In the baseline scenario (Simulation 1) where the wind farm is serviced independently, most of the O&M operations of the 2 GW wind farm was assumed to be performed by 1 service operation vessel (SOV), considered as chartered for the entirety of the wind farm lifetime, with two accompanying daughter crafts. For major component replacement procedures, jack-up vessels (JUVs) were modelled with the assumption that they would be chartered for the duration of the maintenance action, as well as mobilisation and demobilisation periods. For corrective maintenance procedures, 50 corrective maintenance technicians were assumed to be employed on a full-time basis, along with additional 30 technicians chartered periodically for preventive maintenance campaigns. Each wind turbine is assumed to have 6.2 minor repairs, requiring a visit by an SOV, along with 0.1 major component exchanges with a JUV, each year. The maintenance requirements of the wind turbines are detailed in Appendix A.1, along with the corresponding maintenance actions in Appendix A.2.

In the baseline scenario, the O&M of the solar PV farm was assumed to be done with a single SOV, along with 20 dedicated technicians. The maintenance requirements of the solar PV farm is detailed in Appendix A.3, along with the corresponding maintenance actions in Appendix A.4.

The servicing of the CCS platforms was assumed to require the use of a dedicated platform service vessel (PSV), along with 3-4 technicians. This was assumed to occur, for each of the 5 platforms, every 14 days, for 1.5 hours at a time.

The synergy explored in Simulation 2 was the sharing of vessels between the wind farm and the floating solar PV farm. In this simulation, a single SOV was used for the maintenance of both the wind farm and the solar PV farm. Dedicated technicians were also no longer needed, as WTG technicians were assigned to perform maintenance activities on the solar PV farm. Prioritization of maintenance activities was given to the wind farm assets – with solar O&M being performed only when resources were not being used for wind farm O&M, to ensure an efficient allocation of resources given the higher importance of the wind farm. The servicing of the CCS platforms was still assumed to be conducted independently, with dedicated vessels and technicians.

The synergy explored in Simulation 3 was the sharing of vessels and technicians between all three of the included assets: the wind farm, the solar PV farm, and the CCS platforms. In this simulation, neither the solar PV farm SOV nor the CCS platform PSV was needed any longer, and the wind farm SOV and DCs were used instead as the main service vessels for all maintenance activities. Prioritization was given to wind farm maintenance activities, with solar and CCS maintenance being performed only when necessary.

3.3 Scenario Results and Discussion

The following table shows a comparison of the main results found for the chosen simulations.

Table 3-2: Hub West - Scenario Results - Main KPIs

#	Description	Wind Farm Availability [%] (t/y)*	Difference (t/y)	Solar PV Farm Availability [%] (t/y)	Difference (t/y)
1	Wind + Solar	97/98	-/-	95 /91	-/-
2	Wind + Solar (with synergy)	94/95	(-) 3/3	97/91	(+) 2/1
3	Wind + Solar + CCS (with synergy)	94/94	(-) 4/4	97/91	(+) 2/1

(t/y): (time/yield)

As can be seen in the above table, the consequence of synergizing solar O&M activities with wind farm O&M activities results in a decrease in wind farm availability of ~3%, assuming the solar PV farm SOV is no longer used at all. The corresponding increase in solar PV farm availability was found to be 1-2%. The synergized scenario gave full priority to wind farm O&M over solar PV farm O&M, suggesting that without wind farm prioritization, the difference in availabilities would be expected to be much higher.

The following tables shows additional analyses of the potential difference in distances travelled, and emission calculations when synergizing O&M activities. The Tank-to-Wheel (TTW) approach calculated the actual emissions at the vessel released due to consumption, for both diesel and electric vehicles. The Well-to-Wheel (WTW) approach went a step further and calculated the emissions involved in the production of the considered fuel. The total emission reduction values were then calculated by considering these effects along with the individual fuel consumptions of each involved vessel. These calculations were done following the approach used in NSE4 [1] [2]. The first two tables outline the emission reductions possible when conducting O&M using diesel for the service vessels (SOVs and DCs), and the PSV, with the tables afterwards outlining them assuming an all-electric fleet.

Table 3-3: Hub West - Scenario Results – Emission Reductions with a Diesel Fleet (1/2)

		Total Distance Travelled [km/yr]		Total CO2-eq emissions [t/yr] (TTW/WTW)		Total SO2 emissions [10^{-3} t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + Solar	50,497	-	10.98/13.56	-	6.60/20.5	-
2	Wind + Solar (with synergy)	44,094	(-) 13%	6.43/7.99	(-) 41%	3.95/12.0	(-) 40%
3	Wind + Solar + CCS (with synergy)	35,274	(-) 30%	4.68/5.85	(-) 57%	2.92/8.78	(-) 56%

Table 3-4: Hub West - Scenario Results – Emission Reductions with a Diesel Fleet (2/2)

		Total Distance Travelled [km/yr]		Total PM emissions [10^{-3} t/yr] (TTW/WTW)		Total NOx emissions [t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + Solar	50,497	-	4.98/5.49	-	0.23/0.23	-
2	Wind + Solar (with synergy)	44,094	(-) 13%	2.90/3.21	(-) 41%	0.13/0.14	(-) 42%
3	Wind + Solar + CCS (with synergy)	35,274	(-) 30%	2.11/2.34	(-) 57%	0.10/0.10	(-) 58%

Table 3-5: Hub West - Scenario Results – Emission Reductions with an Electric Fleet (1/2)

		Total Distance Travelled [km/yr]		Total CO2-eq emissions [t/yr] (TTW/WTW)		Total SO2 emissions [10^{-3} t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + Solar	50,497	-	0.00/10.02	-	0.00/0.00	-
2	Wind + Solar (with synergy)	44,094	(-) 13%	0.00/5.15	(-) 49%	0.00/0.00	-
3	Wind + Solar + CCS (with synergy)	35,274	(-) 30%	0.00/5.15	(-) 49%	0.00/0.00	-

Table 3-6: Hub West - Scenario Results – Emission Reductions with an Electric Fleet (2/2)

		Total Distance Travelled [km/yr]		Total PM emissions [10^{-3} t/yr] (TTW/WTW)		Total NOx emissions [t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + Solar	50,497	-	0.00/0.92	-	0.00/0.03	-
2	Wind + Solar (with synergy)	44,094	(-) 13%	0.00/0.47	(-) 49%	0.00/0.01	(-) 49%
3	Wind + Solar + CCS (with synergy)	35,274	(-) 30%	0.00/0.47	(-) 49%	0.00/0.01	(-) 49%

The following table outlines the reduction in total labour force requirements found when synergizing O&M activities across multiple assets. In addition, a reduction in total labour and vessel costs is given.

Table 3-7: Hub West - Scenario Results – Cost Reductions

#	Description	Total number of technicians required	Reduction in labour cost [kEUR/yr]	Reduction in vessel costs [kEUR/yr]
1	Wind + Solar	73	-	-
2	Wind + Solar (with synergy)	52	2,100	14,200
3	Wind + Solar + CCS (with synergy)	48	2,500	16,500

3.4 Summary of Hub West Analysis

The simulations showed that sharing vessels and technicians (Scenarios 2 and 3) leads to notable reductions in both operational costs and environmental impacts, although it comes with a slight drop (3–4%) in wind farm availability. Specifically:

- The total number of required technicians dropped by up to 34%.
- Annual labour costs were reduced by €2.5 million and vessel costs by €16.5 million.
- Vessel travel distances decreased by up to 30%, significantly cutting CO_2, NOx, and SO_2 emissions.
- Switching to electric vessels would further reduce carbon and pollutant emissions, bringing some categories close to zero.

The findings highlight that while a minor reduction in wind asset availability occurs, the overall benefits in cost-efficiency, emission reductions, and resource pooling strongly support a combined approach to the logistics and maintenance of offshore energy assets. It can be seen from the above results that the reductions in emissions are not linearly proportional to the reductions in travel distance, as they also depend on which specific vessels have reduced usage, how that usage is synergized across different types of maintenance procedures, and their emissions during non-transiting activities (idling, positioning, etc.).

4 Hub East – Quantitative Analysis

4.1 Scenario Overview

The quantitative analysis run for Hub East focuses on the logistic synergies that can be obtained, when combining resources to operate and maintain offshore wind farm assets, natural gas production at the N05-A platform, and the DEMO 2 electrolysis project. The following table summarizes the simulations performed in Sprint 2.

Table 4-1: Hub East - Scenario Overview

#	Wind Farm Location	Electrolysis Capacity	Natural Gas Platform Location	Resource Synergy
1	Ten noorden van de Waddeneilanden (TNW)	500 MW	N05-A	None
2				Wind + Electrolysis + NG Vessels

The wind farm chosen for this study was the Ten Noorden van de Waddeneilanden wind farm, which is estimated to have a rated capacity of 700 MW. This was chosen due to the planned development of the DEMO 2 project, which is a 500 MW electrolysis project co-located with TNW. The power production of TNW is intended to be used for hydrogen production at DEMO 2, suggesting that maintenance is likely to be shared between these assets. The electrolysis plant is assumed to be located at a single centralized point in the vicinity of the TNW wind farm. In addition, while natural gas production is declining overall in the North Sea, production is planned to continue at the N05-A platform, providing an opportunity for additional logistic synergies. The port chosen for maintenance in this study was Den Helder.

The following figure shows the layout of the relevant assets, where the DEMO2 asset is shown west of the wind farm, and the N05-A platform is southeast.

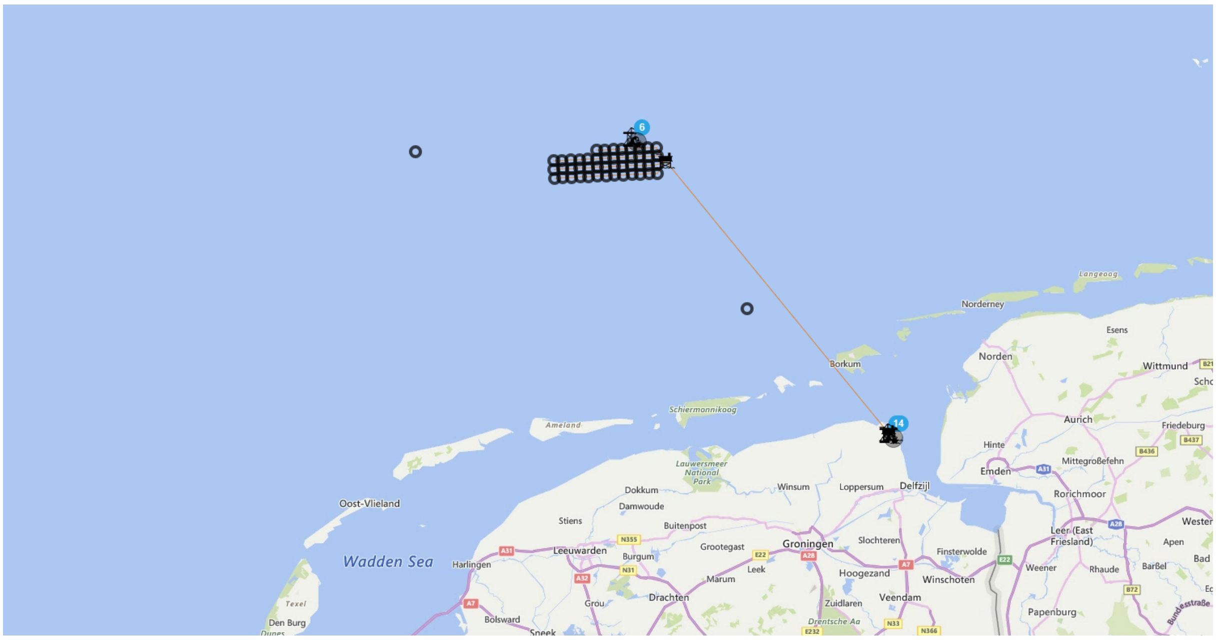


Figure 4-1: Hub East - Graphical Overview

4.2 Logistics Overview

In the baseline scenario (Simulation 1) where the wind farm is serviced independently, the majority of the O&M operations of the 700 MW wind farm was assumed to be performed by a single SOV, assumed as chartered for the entirety of the wind farm lifetime. For major component replacement procedures, jack-up vessels (JUVs) were modelled with the assumption that they would be chartered for the duration of the maintenance action, as well as mobilisation and demobilisation periods. For corrective maintenance procedures, 20 corrective maintenance technicians were assumed to be employed on a full-time basis, along with an additional 10 technicians chartered periodically for preventive maintenance campaigns. As with Hub West, each wind turbine is assumed to require about 6.2 visits by an SOV each year, along with 0.1 visits by a JUV. The maintenance requirements of the wind turbines is detailed in Appendix A, along with the corresponding maintenance actions.

In the baseline scenario, the servicing of the DEMO2 offshore electrolysis plant was assumed to consist of daily maintenance, which requires a visit by 4 technicians every day for 4 hours. In addition, a cell replacement task was assumed to occur every 1.6 years, for 30 days at a time, using an SOV and a heavy lift vessel. These requirements were determined in consultation with project partners and stakeholders.

In the baseline scenario, the unplanned servicing of the N05-A natural gas production platform was assumed to consist of weekly unplanned visits, for 3 hours with 4 technicians. In addition, two 1.5 week maintenance projects were assumed to occur each year, one in each of the spring and the autumn, using 30 technicians and an SOV. An additional yearly painting activity was simulated that requires the use of a heavy lift vessel, and 65 technicians. These requirements were also determined in consultation with project partners and stakeholders.

The synergy explored in Simulation 2 was that of sharing vessels between the TNW wind farm, the DEMO2 electrolysis plant, and the N05-A natural gas production platform. While the daily maintenance of the DEMO2 plant and the weekly unplanned maintenance of the N05-A plant was performed with additional daughter crafts, the DEMO5 cell replacement and bi-yearly natural gas maintenance projects used the TNW SOV. Due to the differences in required skill sets for technicians servicing power equipment and process equipment, a shared group of technicians was considered to service both the DEMO2 and the N05-A assets, separately from the TNW wind farm.

4.3 Scenario Results

The following table shows a comparison of the main results found for the chosen simulations.

Table 4-2: Hub East - Scenario Results – Main KPIs

#	Description	Wind Farm Availability [%] (t/y)	Difference (t/y)
1	Wind + H2 + NG	97/99	-/-
2	Wind + H2 + NG (with synergy)	95/97	1/2

It can be seen from the above results that the wind farm experiences a moderate reduction in availability when the service vessel used to maintain the TNW wind farm is also used to service the DEMO2 and N05-A platform. This is likely due to the relative distance between these assets, combined with the fact that a single SOV is used here, meaning that while it is occupied with its additional tasks at the DEMO5 plant and the N05-A plant, it is unable to service the wind farm, leading to a build-up of component failures.

The following tables shows additional analyses of the potential difference in distances travelled, and emission calculations when synergizing O&M activities. Values were calculated using both Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) approaches, to account for emissions gathered when accumulating the source.

The first two tables outline the emission reductions possible when conducting O&M using diesel for the service vessels (SOVs and DCs), and the PSV.

Table 4-3: Hub East - Scenario Results – Emission Reductions with a Diesel Fleet (1/2)

		Total Distance Travelled [km/yr]		Total CO2-eq emissions [t/yr] (TTW/WTW)		Total SO2 emissions [10^{-3} t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + H2 + NG	84,176	-	13.36/16.61	-	8.22/25.0	-
2	Wind + H2 + NG (with synergy)	42,324	(-) 50%	7.90/9.79	(-) 41%	4.81/14.8	(-) 41%

Table 4-4: Hub East - Scenario Results – Emission Reductions with a Diesel Fleet (2/2)

		Total Distance Travelled [km/yr]		Total PM emissions [10^{-3} t/yr] (TTW/WTW)		Total NOx emissions [t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + H2 + NG	84,176	-	6.03/6.68	-	0.28/0.28	-
2	Wind + H2 + NG (with synergy)	42,324	(-) 50%	3.57/3.95	(-) 41%	0.16/0.17	(-) 41%

The second two tables outline the emission reductions possible when conducting O&M using an all-electric set of service vessels (SOVs and DCs), and PSV.

Table 4-5: Hub East - Scenario Results – Emission Reductions with an Electric Fleet (1/2)

		Total Distance Travelled [km/yr]		Total CO2-eq emissions [t/yr] (TTW/WTW)		Total SO2 emissions [10^{-3} t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + H2 + NG	84,176	-	0.00/14.63	-	0.00/0.00	-
2	Wind + H2 + NG (with synergy)	42,324	(-) 50%	0.00/8.62	(-) 41%	0.00/0.00	-

Table 4-6: Hub East - Scenario Results – Emission Reductions with an Electric Fleet (1/2)

		Total Distance Travelled [km/yr]		Total PM emissions [10^{-3} t/yr] (TTW/WTW)		Total NOx emissions [t/yr] (TTW/WTW)	
#	Description	Total	Reduction	Total	Reduction	Total	Reduction
1	Wind + H2 + NG	84,176	-	0.00/1.33	-	0.00/0.04	-
2	Wind + H2 + NG (with synergy)	42,324	(-) 50%	0.00/0.79	(-) 41%	0.00/0.02	(-) 41%

In contrast to the scenario in Hub West, a reduction in labour force was not modelled, as it was found that the skill set required for electrical work, and that required for work on chemical process equipment, was too dissimilar for technician sharing. The following table outlines the reduction in total vessel costs found when synergizing O&M activities across multiple assets.

Table 4-7: Hub East - Scenario Results – Cost Reductions

#	Description	Reduction in vessel costs [kEUR/yr]
1	Wind + Solar	-
2	Wind + H2 + NG (with synergy)	4600

4.4 Summary of Hub East Analysis

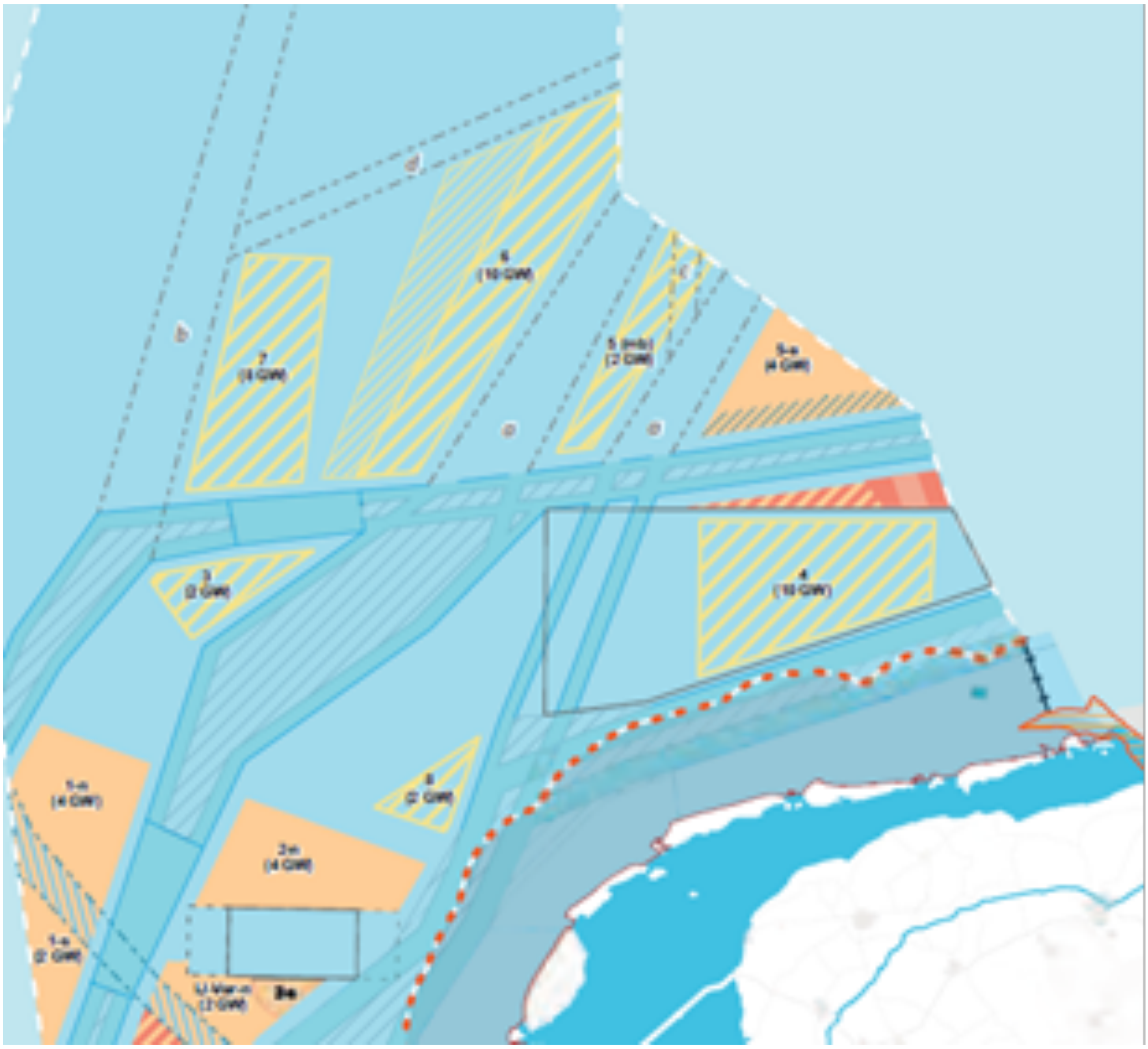
Synergizing vessel operations across the wind farm, hydrogen production, and natural gas platform at Hub East led to a moderate reduction in wind farm availability, with about a 2-percentage-point drop, primarily due to longer vessel occupation times and increased travel distances. However, significant benefits were achieved, as the total distance travelled by vessels was reduced by 50%, leading to a 41% reduction in CO_2 emissions when using diesel-powered vessels, and nearly eliminating direct emissions when using fully electric vessels, with a similar 41% lifecycle emissions reduction. As was seen in Hub West, the relationship between emission cuts and travel distances is non-linear, as the emission reductions are weighted according to the type of vessel, and so the total emission reductions depend on which vessels see reduced usage.

While specialized labour requirements for the tasks considered prevented any reduction in technician workforce costs, the synergy still resulted in substantial financial savings, notably reducing vessel charter costs by approximately €4.6 million per year. Unlike in the Hub West analysis, further reduction of vessel numbers was found impractical, as it caused a disproportionate decline in wind farm availability. Overall, the study demonstrates that while combining logistic activities provides clear environmental and cost benefits, maintaining a careful balance is essential to avoid negatively impacting asset performance.

5 Hub North – Quantitative Analysis

5.1 Scenario Overview

This scenario will focus on the O&M that is assumed to be prevalent in the vicinity of Search Area 6/7 (shown below). As there will be a large focus on offshore hydrogen production, the maintenance of the corresponding hydrogen electrolysis equipment is of key interest here. In NSE5 D1.1 blueprints for Hub North are presented that include a higher and lower end version for offshore wind and hydrogen deployment. The higher end design for Hub North includes 20 GW of wind capacity and 10 GW hydrogen production capacity, while the lower end design includes 14 GW wind capacity and 7 GW hydrogen production capacity.[2]



5-1 Graphical overview of the location of Search Area 6/7

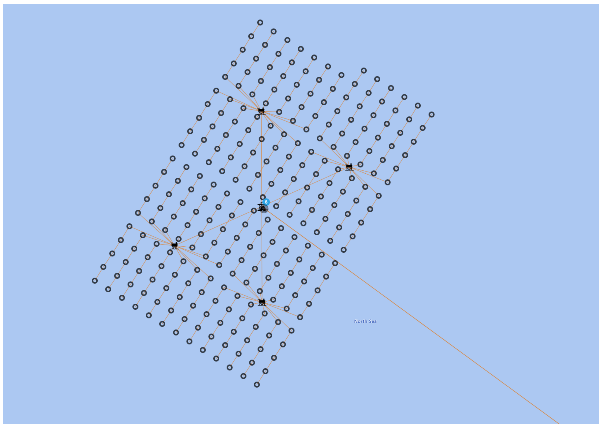
[2] The 20 GW is close to the indicative capacity stated in Partial Revision of the Programme North Sea 2022-2027: "In total, wind energy area 6/7, excluding the open zone, offers space for an indicative 19 GW of wind farms." https://www.rijksoverheid.nl/documenten/rapporten/2025/04/18/bijlage-2-ontwerp-partiele-herziening-programma-noordzee-2022-2027

The quantitative analysis run for Hub North focuses on the O&M logistics for a hydrogen-producing wind farm. In this analysis, a wind farm capable of producing 4.0 GW of power will be considered, with the key difference being in the hydrogen production method. Two scenarios were therefore outlined – the first for when the electrolysis is centralized on 500MW platforms, and a second for when the electrolysis is produced directly at the site of the wind turbine, using a single 12.0MW module per wind turbine, located on an enlarged transition piece deck. An overview of the main scenarios are detailed below. [3]

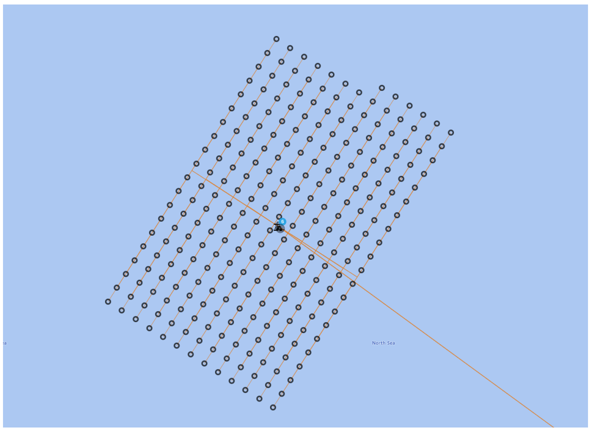
Table 5-1: Hub North - Scenario Overview

#	Description	Power Production		Hydrogen Production	
		Capacity	Location	Capacity	Configuration
1	Centralized Electrolysis	4.0 GW	Search Area 6/7	2.0 GW	4 × 500MW platforms using a module size of 20MW
2	De-centralized Electrolysis	4.0 GW		3.2 GW	1 × 12MW module per wind turbine on an extended transition piece deck

The figures below show the layout of Scenario 1 and Scenario 2, respectively. In Scenario 1, it is assumed that the 4.0 GW wind farm will be split into 4 blocks of an approximately equal size. Each block of wind turbines will feed into its own platform, the output of which all feed into a single export towards shore. It is also assumed that there is, in addition to the 2.0 GW of electrolysis infrastructure, an additional 2.0 GW cabling system in place. In Scenario 2, it is assumed that rows of wind turbines will export hydrogen locally through inter-array piping, which would then also feed into a single export towards shore.



5-2 System layout overview for Scenario 1



5-3 System layout overview for Scenario 2

5.2 Logistics Overview

Both scenarios will include conventional wind turbine maintenance, along with electrolysers maintenance. In both scenarios, wind turbine maintenance is assumed to require technicians

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[3] More information available in NSE5 WP 1 – Technical Innovation report and D1.1-3 Storylines and blueprints for the integration of three NSE hubs in the future energy system of The Netherlands and the North Sea.

with mechanical and electrical skill sets, and electrolysis equipment maintenance is assumed to require technicians with a predominantly process-related skill set. Upon consultation with project partner, it was determined that technicians are unlikely to be trained with both skill sets, so separate teams of technicians will still be required for complete system maintenance.

Both scenarios will require the use of two service operation vessels (SOVs), each with two daughter crafts (DCs) to house these technicians. These SOVs are assumed to be stationed at the vicinity of the wind farm, with port calls every 2 weeks to refill fuel and exchange technician/equipment. Both scenarios will also consider the port of Eemshaven as the main service port for O&M activities and vessel mobilization.

In both scenarios, the wind turbines used are assumed to be the same as in the Hub West and Hub East scenarios. They is assumed to therefore have a rated capacity of 15 MW, and the same set of components. For non-major corrective procedures, 40 corrective wind turbine technicians will be considered employed on a full-time basis, with an additional 30 technicians chartered on a contract basis for yearly preventive maintenance campaigns. Major repairs will be considered the same as with Hub West and Hub East, where jack-up vessels are chartered for the duration of the repair with additional technicians as required by the maintenance action.

In **Scenario 1**, which features **centralized electrolysis** on 4 platforms, each with a 500MW electrolysis capacity, the additional maintenance will be composed of two main parts: monthly module inspections/repairs, and a single stack replacement during the lifetime of the wind farm (assumed to be 25 years).

The monthly inspection/repair of each 20MW electrolysers modules is assumed at this point to require 6 electrolysis technicians, and 4 hours to perform. Given that a platform would house 25 modules, it is assumed that each platform would be permanently manned with 12 technicians.

A stack exchange is assumed to occur once per the lifetime of the wind farm, due to its assumed lower operating lifetime of 80,000 hours, which at a capacity factor equal to that of the wind farm (~50%) would suggest a replacement every 18 years. While an appropriate strategy that reduces concentrations of revenue losses in time would be to spread the 20MW stack replacements throughout the 25 duration of the project, this would lead to inefficiencies in vessel usage, as well as the highest costs due to constant mobilization and demobilization fees. A strategy that focuses on minimizing the number of vessel charters, instead, would be more appropriate. In that case, a barge will be considered that can transport 3000 tonnes, which translates to 100MW of electrolysis equipment (at a conservative estimate of 30 tonnes / MW [3]). This reduces the total number of vessel charters to 5 per platform, or 20 in total.

Assuming the modules are arrange in a ‘plug-and-play’ fashion, where a vessel could arrive with a new module and have it replaced with the old module before returning to port, a platform-attached crane would be required to facilitate the exchange of the stacks. The crane would need to then have a capacity suitable for an electrolysis module that could conservatively weigh 600 tonnes (at 30 tonnes per MW [3]). In this scenario, each stack exchange is assumed to require 36 hours to fully complete. During the repair, production would need to either be rerouted to other modules, exported as power, or curtailed during periods of rated production.

In **Scenario 2**, which features **de-centralized electrolysis** though 12MW modules placed on an extended transition piece deck, the additional maintenance requirements are similarly assumed to be composed of two main parts: an inspection/repair every 6 months, as well as a stack exchange once in the lifetime of the wind farm. The difference in maintenance requirements between inter-array cabling and inter-array piping is not considered in these simulations.

The periodic electrolysers inspection/repair is assumed to require 4 electrolysis technicians, and 4 hours to perform. These technicians will be drawn from a pool of 24 additional technicians, assumed to be employed full time, and stationed on the same vessels as the wind farm technicians.

Given that a heavy lift vessel with a crane capacity of up to 360 tonnes is required, a jack-up vessel will be used to perform these stack exchanges. It is assumed that this set of stack exchanges will be performed once, with the vessel being mobilized for a set of campaigns within which 18 wind turbines would be serviced at a time.

5.3 Scenario Results

An overview of the system availability can be seen below.

Table 5-2: Hub North - Scenario Results – Main KPIs

#	Description	System Availability [%] (t/y)	Availability loss due to inspections [%] (t/y)	Availability loss due to stack replacement [%] (t/y)
1	Centralized Electrolysis	96/96	0.6/0.6	0.1/0.1
2	De-centralized Electrolysis	91/91	5.0/5.0	0.1/0.1

Of the two scenarios, it can be seen that the de-centralized approach to hydrogen production leads to significantly lower availabilities, which can largely be attributed to the requirement of having regular inspections. Even with the assumption of less frequent inspections (6 months in the de-centralized approach vs. 1 month in the centralized approach), it is the requirement that a technician team would need to transit to the wind turbine to perform the inspection, that leads to this difference.

In the de-centralized scenario, where the inspections are performed by a technician team stationed in the shared SOVs, the technicians must transit to the wind turbine to perform this inspection. This is subject not only to the limitation that these vessels are not in the midst of performing other wind turbine maintenance work, but the additional weather-related conditions that the repair itself must be performed in. This includes the limitations under which the vessel can transit, as well as the safety requirement that states that an emergency removal of the technicians must be possible while the technician is on the wind turbine. As the frequency of the electrolyser inspections may reduce over the years due to reliability improvements, it would then be expected that the availability of the system will approach that of a conventional power-producing wind farm of comparable size.

Comparatively, the maintenance strategy is easier to perform given a centralized scenario because the technicians are already at the site of the platform, and do not rely on vessel availability to perform their tasks. The fact that vessels are not a part of the inspection/repair strategy at all further gives the benefit that the tasks are also weather-independent.

The stack replacement strategies impose less of a loss in availability, largely due to the ability of the vessels to perform in harsher weather conditions. In addition, these operations are assumed to require an independent set of vessels and technicians, which are assumed to be chartered in advance. Given the assumption that the electrolyser stacks are in operation until the required vessel arrives with the new stack, this means that downtime is limited to the actual time required to disconnect the old stack, replace it with the new stack, and connect that new stack. Given that this operation can be planned flexibly and far in advance, assumed here in summers, weather conditions were found to be unlikely to present operational challenges.

The differences in resource costs for these two strategies can be found in the table below.

Table 5-3: Hub North - Scenario Results – Cost KPIs

#	Description	Yearly vessel cost [M€]	Yearly technician cost [M€]
1	Centralized Electrolysis	5.3	4.8
2	De-centralized Electrolysis	6.7	2.4

The above table shows the estimated costs of performing electrolysis maintenance for the 4.0 GW wind farm, in addition but not including the existing costs of performing wind farm maintenance. The centralized approach shows how the additional vessel costs for the centralized approach outweigh those for the de-centralized approach, largely due to the lower electrolysis capacity that would be present for that scenario (2.0 GW vs. 3.2 GW). Higher electrolysis capacities would be expected to increase vessel costs, due to the increased number of charters required (assuming equal vessel-carrying capabilities). In the event of increased vessel capabilities, the higher costs of chartering these larger vessels could be balanced out by the reduced number of total charters required.

The estimated technician costs are larger, however, for the centralized scenario, due to the higher number of technicians that are assumed to be contracted. This is subject to change as platforms are expected to become unmanned in the future, with regular inspections less frequent. This latter possibility is valid for both scenarios, with a potential for high cost reductions if the additional electrolysis maintenance (which would anyways draw from an independent pool of technicians) were to be performed by a single party for the entirety of Hub North.

5.4 Summary of Hub North Analysis

The results of the studies performed in Hub North suggest that of the two scenarios studied in Hub North, both would likely have higher downtimes and higher costs compared to conventional power-producing wind farms, due to the additional O&M requirements of the electrolysis systems. The results suggest that the differences in downtime and costs will continue to be a factor of the type of maintenance strategies that will evolve, but this would need to be proven through additional studies.

With the current assumptions detailed in this report, the centralized electrolysis option offers higher availabilities due to the centralization of the electrolysis equipment and the on-site personnel. This allows a much higher level of weather-independence, as well as a de-coupling from conventional wind turbine O&M. The lower electrolysis capacity (2.0 GW assumed here) also played a factor in the comparison between the scenario results, although it is likely that even with the same capacity, centralized electrolysis O&M would be easier to perform. These factors also play a role in how expensive the hydrogen-producing wind farm system is to maintain, with lower costs for the centralized approach for stack-exchange vessels. The higher technician costs are subject to the requirements of the electrolyser maintenance in the future - if platforms in the future are not required to be manned, and perhaps are operated by a single entity, costs would be expected to reduce significantly.

6 Conclusions

This study focused on the logistic implications that could be identified as a result of the Hub blueprints developed in and passed from WP1. Following that structure, this work was conducted by first defining independent sets of scenarios according to the technologies and timelines expected for Hub West, East and North.

In Hub West, the logistic benefit of synergizing resources to perform O&M on offshore wind farms, offshore solar PV farms, and CCS platforms was quantified, and showed that reducing and synergizing O&M assets could lead to technician and vessel cost savings on the order of €19 million per year and a reduction in required technicians by 34%, but with a resulting drop in wind farm availability of 3-4%. In Hub East, the logistic benefit of synergizing vessels for the combined O&M of offshore wind, hydrogen production, and natural gas production was found to give annual cost savings of €5 million, while technician synergies were not found to provide benefits largely due to the difficulty in their cross-skilling. In Hub North, the logistic differences in performing O&M on centralized and de-centralized offshore electrolysis for hydrogen production were explored, with distinct maintenance strategies defined for each of those two cases. Large differences in availability and costs were found, with the major driving factors identified as the high vessel cost of stack exchanges, and the downtime required for regular inspections.

Some key conclusions can be summarized here, with more details in the appropriate section conclusions:

- Synergizing resources while reducing the overall pool of resources led to significant cost savings, at the expense of power production availability, suggesting that further refined strategies could focus on compensating for the latter.

- Synergizing vessel fleets resulted in large reductions in travel times (30-50%), and corresponding large reductions in emissions of CO2, SO2, and NOx. Nitrogen emissions are especially relevant in the Dutch context, where infrastructure projects close to sensitive areas are subject to additional scrutiny thereof.

- Reductions in technician requirements were found to have more potential between offshore wind and offshore solar, but less potential with offshore hydrogen production with electrolysis. However, potential benefits could still be realized, such as with de-centralized hydrogen production where these assets are co-located at the wind turbine.

- In general, the requirements of offshore electrolysis maintenance are still unknown, and may therefore be subject to significant improvements over the coming decades. Operational learnings could supplement further research significantly.

7 Future research directions

7.1 Automation & Robotization in O&M

The main findings from the simulations conclude that there are significant cost savings and technician reductions possible with asset sharing and synergies, but with the risk that if not done with careful & strategic planning, it could lead to loss of asset availability. This is due to the long waiting periods for the vessels and technicians which are occupied attending to the failures of other assets. This challenge could be optimized with the deployment of autonomous drones for inspections/ robots for repair or unmanned survey vessels for underwater asset surveys. This frees up the current pressure on vessels and technicians leading to an optimized O&M synergy.

7.1.1 Ecological Impact

In interviews with stakeholders, it was identified that the main ecological concern related to the O&M of offshore wind farms was the noise emissions produced by vessels during their activities in the wind farm. Detailed research showing the quantitative effect of noise on the wildlife is not yet present at the current moment, however noise reduction can be quantified at the vessel level. Given modern maintenance requirements and the technician-centric methods with which they are maintained, there is an opportunity for significant noise reduction when maintaining a wind farm.

One method involves reducing the emissions of the related vessels, such as by equipping them with both main and auxiliary engines, the latter of which if electrically powered, would be quieter. The louder main engines could be reserved for high-speed travel outside the wind farm boundary, and the electric auxiliary engines could be reserved for slower travel within. This would result in higher upfront costs due to the added complexity of vessel design, but would be unlikely to present operational drawback as vessel speed within the wind farm would need to be lower regardless.

Another method is with reducing the number of visits required for the wind farms themselves. Current methods of maintaining wind farms rely heavily on the use of technicians, which require vessels for transport. Using more robotics and autonomous vessels for maintenance could lead to less visits per year, reducing the amount of noise emitted. Automation and robotization in wind farm logistics could bring following benefits from ecological perspective:

1. Lower Carbon Emissions: Autonomous electric vehicles and drones replace diesel-powered machinery, thus reducing emissions. Also fewer on-site personnel reduce travel and accommodation-related emissions.
2. Lowering Nitrogen Emissions: The success of projects, especially those in proximity to protected areas, are subject to their expected nitrogen-related impact. Optimized maintenance strategies could play a role in reducing the potential thereof.
3. Reduced Waste and Material Use: Precision robotics can minimize damage to large turbine components during handling, thus significantly reducing waste.

4 Minimized Land and Habitat Disruption: Drones and robotic systems reduce the need for heavy machinery and personnel on-site, causing less disruption to flora and fauna. Remote monitoring limits frequent human access, helping preserve local ecosystems.
5 Cleaner Decommissioning and Recycling: Automated dismantling and sorting streamline recycling at end-of-life, reducing landfill impact and transportation emissions

7.1.2 Human Capital

Shortage of trained offshore technicians is a critical bottleneck globally and O&M requires highly skilled technicians with expertise in:

1 Mechanical and electrical systems
2 Digital monitoring tools (SCADA, sensors, drones)
3 Health & safety protocols for working at height and in remote locations

Remote and harsh working environments leads to logistical challenges, fatigue, and retention issues among the workers and thus causing increased pressure on workers' mental and physical health. Also, a significant portion of the existing O&M workforce is aging.

Automation and robotization can help alleviate this shortage, by:

1 Reduces Demand for Manual Labor: Robots and automated systems handle repetitive or hazardous tasks such as heavy component handling and routine inspections which lowers the need for a large manual workforce, easing the pressure on technician numbers.
2 Extends Workforce Productivity: Available technician force can be strategically employed improving the efficiency of overall operations.
3 Enables Leaner, Smarter Operations: Fewer but more skilled technicians are needed to maintain automated systems, rather than doing the physical tasks themselves. This reduces the strain caused by the global shortage of general wind logistics personnel.

The assessment performed in Hub West indicates that the skill-set requirements for wind farm technology and solar PV farm technology, which are both primarily mechanical and electrical in nature, are likely to overlap effectively, leading to a high potential for savings through the use of cross-skilled technicians. The corresponding assessment for hydrogen-producing electrolysis technology, which is primarily process-related in nature, has a lower likelihood of effective overlap. O&M savings through the use of cross-skilled technicians would therefore be less likely to occur, although still worth investigation. For example, de-centralized electrolysis configurations, which would otherwise require drawing from two distinct pools of technicians, could benefit from this synergy, although this would need to be proven through further analysis.

In general, the O&M strategies related to offshore hydrogen production through electrolysis are largely unknown, and will be developed and refined over the coming years. In this study, centralized electrolysis platforms were considered manned, and scenarios considering unmanned platforms were not considered. Shifting towards unmanned scenarios is worth exploring due to the implications for human capital, both to relieve pressure on the labour market but also to realize cost savings. Robotics and automation have the potential to contribute to this shift.

More information on human capital challenges and possible solutions is provided in NSE5 D2.1

7.2 Data Sharing

A topic highly related to asset sharing is the data sharing aspect in logistics and operations. The importance of data sharing across multiple asset owners in offshore operations and logistics is growing rapidly as offshore wind farms scale in size, complexity, and stakeholder diversity. When multiple asset owners operate within the same offshore region (e.g., shared ports, vessels, or grid infrastructure), data sharing becomes essential for maximizing efficiency, safety, and cost-effectiveness. This leads to:

4. Optimized Resource Utilization: Joint planning of logistics operations enables optimized resource allocation, thus reducing vessel trips and fuel consumption
5. Improved Situational Awareness: Each asset owner may operate different wind farms, but all depend on weather conditions, maritime traffic and offshore infrastructure availability. Sharing this data gives all parties a real-time, common operational picture, reducing conflicts and improving decision-making.
6. Predictive and Preventive Maintenance: Asset owners benefit from shared condition monitoring data (e.g., turbine health, failure patterns). Cross-company analytics improve maintenance timing, component lifespan predictions and logistics planning for spare parts and technicians.
7. Supply Chain Coordination: Asset owners often share logistics contractors, ports, and warehouses.
   Data sharing enables more accurate scheduling, reduced idle time and better inventory management across multiple owners.
8. Safety and Emergency Response: In emergencies (e.g., accidents, extreme weather), shared safety protocols and personnel tracking data ensure coordinated response across sites. Faster, more effective evacuation and support operations rely on common situational data.
9. Environmental and Regulatory Compliance: Regulators increasingly require transparent reporting of emissions, vessel use, and marine impacts. A shared data environment streamlines joint compliance reporting, cumulative environmental impact assessments.

In WP2, the projection of the Dutch labour market was researched, along with its impact on the Dutch ambition for offshore energy development. It's clear that either the labour force must increase drastically, opportunities to reduce technician requirements must be found, or some combination thereof. Given research into O&M strategies that share technicians across various assets, the human capital savings for specific scenarios can be determined by modelling scenarios with and without this sharing. Extrapolation of these scenarios could lead to a better understanding of the impact of technician sharing for the entirety of the Dutch North Sea.

For O&M, these synergies depend on the skills sets required to maintain these assets, which differ depending on which asset is being considered. The largest difference in skill set is between electrons and molecules, suggesting that synergies are likelier to occur between offshore wind and offshore floating solar farms, or between electrolysis and natural gas production. Synergies can also be realized between neighbouring offshore wind farms that are operated by different parties. At the moment, the resource pooling experienced in the natural gas production sector, performed in large part by ONE Peterson, is not found in the offshore wind sector. Strict confidentiality measures currently prevent this, suggesting that secure data transfer methods may need to be developed. The potential benefits of this type of synergy have not yet been investigated fully.

North Sea Energy D5.2 provides and overview of advanced data sharing options from existing practices and case studies. This paper also indicates what next steps could be taken in this domain.

7.3 Refined Maintenance Strategies

7.3.1 Scenario Definition

The scenarios in this study were defined according to the assumptions in work package 1 of the NSE program, and were simulated accordingly. The scenarios themselves may change in the next phase of the NSE program (NSE6) according to the evolution of the development in the North Sea, and the maintenance strategies may need to adapt accordingly. This can also be due to the new learnings that may be acquired from upcoming operational experience. For example, oil and gas development was not considered in Hub North in this study, although that may change and present logistic challenges and opportunities accordingly for exploration in NSE6. Carbon capture and storage technologies were also not considered in Hub North, which could also be explored in NSE6.

For all the hubs, the maintenance strategies could be refined, either through the strategies explored above or through the consideration of improvements in vessels and technologies. Automation and robotization, as described above, is an example of this, but improving existing vessels, or incorporating new vessels types such as helicopters, into cross-asset maintenance, could improve the overall maintenance costs.

Also in the Hub North , currently maintenance strategies for Oil & gas platforms involving helicopter logistics have not been considered. Studies from EBN has shown that there could be spatial conflicts for carrying out the current logistics patterns using helicopters as this creeps in to wind and CCS areas. Combining logistics for various operators and creating a common logistics pool , involving vessels and technicians, could be a way forward to mitigate this challenge.

Another refinement could be in the expansion of the scope of holistic logistics strategies, both in terms of the type of asset, but also in terms of port selection and geographical location. For example, if Dutch asset O&M could be performed by non-Dutch parties operating out of non-Dutch ports, this could lead to overall system savings. This is also true in terms of installation and decommissioning strategies, for which port selection is an important factor. These are all possible research directions for NSE6.

7.3.2 Alternative Fuels

As part of the research done in NSE4, emission data related to the maintenance campaigns for wind farms and CCS platform maintenance was calculated. The vessels considered for that analysis were fuelled by electric power, hydrogen, heavy fuel oil (HFO) with a scrubber to partially offset emissions, and liquified natural gas (LNG). Calculations of the Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) emissions were performed for maintenance campaigns with and without resource synergies between the offshore wind farms and platforms, to investigate the emission savings that resulted from that synergy. In NSE5, similar calculations were performed to quantify the corresponding emission cuts that occur with reduced travel distances, considering both diesel and all-electric fleets.

While these fuels are likely to make an appearance in the North Sea, it is not yet clear which fuel will power the majority of the vessel fleet in the North Sea. Other possible fuels that could be investigated include ultra-low-sulphur diesel (ULSD), ethanol, ammonia, gas-to-liquid (GTL), or any of a large variety of bio-fuels, such as hydrotreated vegetable oil (HVO). Some of these options still exist only in their research phase, such as sodium borate nitrate, which is considered to be a candidate for hydrogen propulsion from a solid-state material. In NSE6, these alternative fuels can also be considered and explored to find additional emission reduction potentials.

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Appendix A: Logistics Details

A1. Offshore Wind Farms – Subsystem Breakdown

The offshore wind farms, simulated using the UWiSE O&M Planner tool, were assumed to have the subsystem breakdown as follows. Each subsystem was assumed to have up to three failure modes, each with an associated corrective maintenance action, a set of required resources, and the repair duration considered in the method statements of Appendix A.2.

Direct-drive generator

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Complete failure	Complete replacement	1 JUV 8 JUV Technicians

Main bearing

Failure Modes	Associated Action	Resources Required
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 JUV 17 JUV Technicians

Power converter

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 2 WTG Technicians
Complete failure	Complete replacement	1 JUV 6 JUV Technicians

Blade

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 JUV 21 JUV Technicians

Pitch system

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 JUV 4 JUV Technicians

Yaw system

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 JUV 5 JUV Technicians

Electrical components

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 SOV 4 WTG Technicians

Grease/oil/cooling liquid

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians

Contactor/circuit/breaker/relay

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 SOV 8 WTG Technicians

Controls

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 SOV 2 WTG Technicians

Safety

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians

Sensors

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 2 WTG Technicians

Pumps/motors

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians

Hub

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 4 WTG Technicians
Complete failure	Complete replacement	1 JUV 10 JUV Technicians

Heaters/coolers

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians

Service items

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 2 WTG Technicians
Major failure	Major repair	1 SOV 2 WTG Technicians

Transformer

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 3 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians
Complete failure	Complete replacement	1 JUV 5 JUV Technicians

Tower/foundations

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 3 WTG Technicians
Major failure	Major repair	1 SOV 3 WTG Technicians

Inter-array cables

Failure Modes	Associated Action	Resources Required
Complete failure	Complete replacement	1 CLV 10 CLV Technicians

A2. Offshore Wind Farms – Method Statements

For minor and major failures requiring the use of an SOV, the method statement shown in the first table describes the procedure simulated by UWiSE O&M Planner. During simulation, work orders stemming from these maintenance actions are grouped together – meaning that the stages of the resulting work orders are planned such that a single vessel visits multiple systems, distributing technicians and equipment as necessary, and collects them back at the end of the day. This is contrast to major maintenance actions, in which the associated vessel is assigned solely to the execution of that maintenance action, and doesn't become available until that action is complete. The simulated steps of major maintenance procedures are highlighted in the second table.

Stage	Step	Operational Details	
Preparation	Transit to system	SOV Vessel Speed:	12 knots
		SOV Operational Limits:	Significant wave height < 2.5m Wind speed at 10m < 15.0 m/s
	Transfer resources	Duration:	1 hour
		Operational Limits:	Hs < 2.0m
Activity	Turn off system	Duration:	-
	Repair system	Duration	Depends on subsystem and task
	Turn on system	Duration:	-
Finish	Transfer resources	Duration:	1 hour
		Operational Limits:	Hs < 2.0m
	Transit to port	SOV Vessel Speed:	12 knots
		SOV Operational Limits:	Significant wave height < 2.5m Wind speed at 10m < 15.0 m/s

Step	Operational Details	
Load vessel at port	Duration:	1 hour
Transit to the system	JUV Vessel Speed:	10 knots
	JUV Operational Limits:	Significant wave height < 3.0m Wind speed at 10m < 15.0 m/s
Unload vessel at the system	Duration:	1 hour
	Operational Limits:	Hs < 2.0m
Turn off system	Duration:	-
Replace system	Duration	Depends on subsystem and task
	Operational Limits:	Depends on subsystem and task
Turn on system	Duration:	-
Load vessel at the system	Duration:	1 hour
	Operational Limits:	Hs < 2.0m
Transit to port	JUV Vessel Speed:	10 knots
	JUV Operational Limits:	Significant wave height < 3.0m Wind speed at 10m < 15.0 m/s
Unload vessel at the system	Duration:	1 hour

A3. Offshore Solar PV Farms – Subsystem Breakdown

The offshore floating solar PV farms, simulated using the UWiSE O&M Planner tool, were assumed to have the subsystem breakdown as follows. Each subsystem was assumed to have up to three failure modes, each with an associated corrective maintenance action, a set of required resources, and the repair duration considered in the method statements of Appendix A.4.

Floater assembly

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 5 PV Technicians
Major failure	Partial replacement	1 SOV 7 PV Technicians
Complete failure	Complete replacement	1 SOV & 2 Tugboats 7 PV Technicians

Central inverter

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 10 PV Technicians
Component failure	Complete replacement	1 SOV & 2 Tugboats 10 PV Technicians

Transformer

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 10 PV Technicians
Complete failure	Complete replacement	10 PV technicians

Mooring assembly

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 10 PV Technicians
Line Failure	Complete replacement	SOV & 2 Tugboats 10 PV Technicians

Additional cabling

Failure Modes	Associated Action	Resources Required
Minor failure	Minor repair	1 SOV 3 PV Technicians

A4. Offshore Solar PV Farms – Method Statements

Similarly to the wind farm, work orders stemming from maintenance actions that require the use of an SOV were grouped together, and are shown in the first table, while larger major maintenance actions, that require the additional use of tugboats, are shown in the second table, and are planned independently.

Stage	Step	Operational Details	
Preparation	Transit to system	Vessel Speed:	12 knots
		Operational Limits:	Significant wave height < 2.5m Wind speed at 10m < 15.0 m/s
	Transfer resources	Duration:	1 hour
		Operational Limits:	Hs < 2.0m
Activity	Turn off system	Duration:	-
	Repair system	Duration	Depends on subsystem and task
	Turn on system	Duration:	-
Finish	Transfer resources	Duration:	1 hour
		Operational Limits:	Hs < 2.0m
	Transit to port	Duration:	Dependent on vessel speed
		Operational Limits:	Dependent on vessel weather limits

Step	Operational Details	
Organize inspection	Duration:	6 hours
Transit to the system	SOV Vessel Speed:	12 knots
	SOV Operational Limits:	Significant wave height < 2.5m Wind speed at 10m < 15.0 m/s
Unload vessel at the system	Duration:	1 hour
	Operational Limits:	Hs < 2.0m
Perform inspection	Duration:	4 hours
Load vessel at the system	Duration:	1 hour
Organize the replacement	Duration:	16 hours
Load the tugboats at port	Duration:	1 hour
Transit the tugboats to the system	Tugboat Vessel Speed:	3 knots
	Tugboat Operational Limits:	Significant wave height < 3.0m Wind speed at 10m < 12.0 m/s
Unload tugboats at the system	Duration:	1 hour
Turn off system	Duration:	-
Replace system	Duration	Depends on subsystem and task
Turn on system	Duration:	-
Load all vessels at the system	Duration:	1 hour
	Operational Limits:	Hs < 2.0m
Transit all vessels to their base	Duration:	Dependent on vessel speed
	Operational Limits:	Dependent on vessel weather limits
Unload tugboats at port	Duration:	1 hour

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