Offshore Wind Farm Decommissioning Cost Estimates

Simulating removal and transport of the subsystems of a hypothetical offshore wind farm site representative for the Dutch Roadmap 21GW

TNO Public ⟩ TNO 2025 R11554

13 November 2025

Energy & Materials Transition
www.tno.nl
+31 88 866 80 00
info@tno.nl

TNO 2025 R11554 – 13 November 2025

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Author(s)	S. Mancini, J. Bloothoofd, G. Donnelly
Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Appendices	TNO Public
Number of pages	59 (excl. front and back cover)
Number of appendices	2
Sponsor	Ministerie van Klimaat en Groene Groei (KGG)
Project name	Research into the absolute costs of decommissioning an offshore wind farm
Project number	060.66012

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Executive Summary

The Dutch Ministry of Climate and Green Growth (KGG) commissioned TNO to provide updated cost estimates for the removal and transport of offshore wind farm subsystems. These estimates are intended to inform revisions to the financial security provisions in future Wind Farm Site Decisions (WFSDs) under the Dutch Roadmap 21GW. Additional context is provided in Chapter 1.

This report summarizes the outcomes of high-fidelity simulations conducted with **TNO's UWiSE Decommission** software to estimate offshore wind farm decommissioning costs. The simulations cover the removal and transport of wind turbine generators (WTGs), inter-array cables (IACs), monopile foundations (MPs), secondary steel components, and scour protection layers (SPLs), as well as associated pre- and post-decommissioning activities. Multiple scenarios were analyzed, including a baseline case, variations in farm size and turbine rating, port distance sensitivity, and activity duration uncertainty. Input assumptions reflect current knowledge and price levels. Given the long-term horizon of these campaigns, the analysis also considers emerging removal technologies that are not yet widely deployed but have been validated in relevant environments and have credible development roadmaps aligned with industry needs (e.g., large-scale vibro-removal and internal cutting of 8–10 m diameter monopiles). Chapter 2 elaborates on the approach and assumptions used in this study, while Chapter 3 presents the key simulation inputs.

Key findings include:

- Baseline **full removal costs** are estimated at **172.5 k€/MW**, while **partial removal costs** are **110.6 k€/MW** (incl. cutting foundations 6 m below seabed and leaving cables and scour protection behind).
- **Scour protection removal** is the largest cost contributor, accounting for nearly 40% of full removal costs and driving the difference compared to partial removal.
- **Smaller farms** exhibit higher €/MW costs due to reduced economies of scale.
- **Larger turbines** reduce €/MW costs due to economies of scale despite requiring larger vessels for wind turbine removal.
- **Port distance** has a moderate impact on costs, with SPL and MP campaigns most affected.
- **Activity durations** are a major sensitivity factor due to the large uncertainty induced by limited field experience, with pessimistic assumptions increasing costs by up to 45%.

The limited real-world experience with utility-scale offshore wind decommissioning required many expert-based assumptions that carry inherent uncertainty. Nonetheless, the methodology employed and results provide up-to-date insights and robust inputs for informed policy choices.

TNO recommends using these estimates as indicative averages for WFSDs, while allowing flexibility for site-specific deviations. Allowing periodic reviews of bank guarantee amounts is advised to reflect market developments and technological progress.

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Appendices

1 Introduction

1.1 Background

When developing new offshore wind farms in the Dutch North Sea, project developers are required by the Dutch Government to arrange a bank guarantee for the decommissioning of the site. This requirement is intended to protect society from the financial risks associated with default and abandonment. The amount of the bank guarantee is specified in the official Wind Farm Site Decision (WFSD – *kavelbesluit*) for each site. A value of €120,000 per MW was established in the WFSD for Borssele I-II in 2016 [1], and it has remained unchanged since its introduction.

Recent research and feedback from market stakeholders have indicated that the current bank guarantee may not provide sufficient security to ensure future compliance with decommissioning obligations (e.g. [2], [3], [4]). A recent report commissioned by the Dutch Ministry of Climate and Green Growth (KGG) called for an urgent revision of the bank guarantee amount, based on updated decommissioning cost estimates [5].

In response, TNO was commissioned by KGG to estimate the expected decommissioning costs for offshore wind farms included in the Dutch Roadmap 21GW [6]. These estimates will inform the revision of bank guarantee requirements in upcoming WFSDs.

The formal assignment was received on 7 July 2025, and the underlying assumptions and inputs were reviewed in a workshop with relevant industry stakeholders on 24 September 2025. The present report constitutes the final deliverable of the assignment.

1.2 Goal and structure of the report

This report presents the results of TNO's analysis of the expected costs for the removal and transport of the various subsystems of a hypothetical offshore wind farm representative of the new sites planned under the Roadmap 21GW.

The aim is to provide KGG with up-to-date cost estimates to support the revision of decommissioning security provisions in future WFSDs. By analyzing the removal and transport costs of individual subsystems, the report enables KGG to assess the expected costs of both full and partial removal strategies.

The report is structured as follows:
- Chapter 2 discusses the scope, methodology, and key assumptions of the study.
- Chapter 3 outlines the main input parameters used in the analysis.
- Chapter 4 presents the baseline simulation results.
- Chapter 5 summarizes the main conclusions and recommendations.
- Appendix A lists the key attributes of the reference sites considered.
- Appendices B-E contain the results of simulation scenarios other than the baseline.
- Appendix F provides supplementary information on the statistical spread of the cost estimates due to yearly weather variability and seasonality effects.

1.3 Essential Context

To ensure a correct interpretation of the contents of this report, the following important remarks should be considered:

Uncertainty in assumptions

At the time of this study, global experience with utility-scale offshore wind farm decommissioning is extremely limited. No standard removal methods, processes, equipment, or guidelines have been established [7]. Therefore, in order to estimate removal and transport costs, several expert-based assumptions were necessary regarding decommissioning procedures, durations, and weather dependencies. TNO made its best effort to ensure these assumptions are as realistic and grounded on state-of-the-art knowledge levels as possible, using both internal expertise and inputs gathered via a well-attended workshop with industry experts. However, lacking real-life validation at scale, these assumptions inherently carry high uncertainty and should be revisited periodically as new knowledge and experience are generated.

Site-specific nature of decommissioning costs

Decommissioning costs for offshore wind farms are highly site-specific, influenced by factors such as wind farm size, turbine rating and diameter, soil characteristics, water depth, local metocean conditions, and proximity to ports. Therefore, a single cost figure cannot accurately represent all sites in the Roadmap 21GW. TNO understands that KGG seeks a reasonable average cost estimate, along with an indication of potential site-to-site variation. Ideally, each site in the Roadmap would be assessed individually to derive a comprehensive statistical overview. However, this was not feasible within the schedule and budget constraints of this assignment, and thus representative hypothetical sites (described in Chapter 2) were considered instead.

Independent assessment

TNO is an independent organization dedicated to applied scientific research. Accordingly, this assessment was conducted without bias toward specific removal strategies, technologies, or equipment. All the choices and assumptions made were based solely on technical considerations and the best available knowledge of the authors, free from any conflicting interests. While certain processes or equipment referenced in this report may be associated with specific commercial entities, their inclusion serves only to illustrate existing technological options. TNO does not endorse or favor any particular supplier or product. Mentions of commercial items, such as vessels or turbine models, are intended purely as concrete examples to support the analysis. Under no circumstances should the assumptions or references in this report be interpreted as technical recommendations or endorsements of specific removal strategies, technologies, or suppliers.

Scope of the analysis

The present study focuses exclusively on the estimation of costs and duration of wind farm removal and transport operations. Other equally important aspects such as environmental and ecosystem impacts of decommissioning or circularity performance are outside the scope of this analysis and have not been considered.

2 Methodology

2.1 Key challenges

KGG commissioned TNO to estimate the expected decommissioning costs for offshore wind farms in the Roadmap 21GW, to inform future WFSDs. Given current knowledge levels, this task presents the following key challenges:

A. Limited field experience available from past projects

To date, the only offshore wind decommissioning project executed in the Netherlands is the wind park Lely [8], a small-scale farm of 4x2MW turbines located in the IJsselmeer (inland waters). Globally, only a few small-scale offshore wind farms have been dismantled, none of which are representative of the scale, technology, or environmental conditions of the modern sites in the Roadmap 21GW [9] [10]. While the Oil & Gas sector offers relevant experience, offshore wind farms present unique challenges requiring specialized technologies and methodologies [11]. To cope with this challenge, expert-based assumptions have been formulated and reviewed as described in Section 2.5.

B. Site-specificity

As discussed in Section 1.3, decommissioning costs are highly site-specific, influenced by factors such as wind farm size, turbine design, soil conditions, metocean data, and proximity to infrastructure, among others.

C. Strong dependency on long-term developments

Decommissioning is expected to occur at the end of the permit period (currently 40 years). Estimating costs over such a long horizon is inherently uncertain, and further complicated by:

1. **Market volatility**: Decommissioning costs are heavily dependent on highly fluctuating market conditions such as day rates of specialized vessels and equipment, which are driven by supply-demand dynamics that are difficult to predict.
2. **Technological advancements**: The offshore wind decommissioning market is still in its infancy, and future innovations may significantly alter removal methods and logistic strategies.
3. **Regulatory changes**: Evolving national, EU, and international regulations [12] may affect decommissioning scope and processes, ultimately affecting costs.
4. **Climate change impacts**: global warming could affect weather-related operational risks and associated costs during decommissioning.

D. Uncertain revenue streams offset costs

The overall economic balance of an offshore wind farm decommissioning project includes revenue streams associated with the sale of end-of-life (EoL) subsystems, components, or materials to new end users, as well as revenues potentially generated by the production of electricity from active parts of the farm during the execution of the initial phases of the decommissioning campaign. EoL-related revenues are currently unpredictable as they depend on the specific EoL route selected for each subsystem/component/scrap material and the future cost structure and price levels of EoL businesses, which are still in their early infant stage of development. Production-related revenues are also difficult to predict as they are highly dependent on future offtake price levels as well as the specific decommissioning project schedule.

E. **Proprietary intellectual property**
Cost and performance data of specialized vessels and decommissioning equipment, as well as detailed process descriptions of decommissioning methods, may be sensitive industrial intellectual property of commercial parties and thus not publicly available. To cope with this challenge, expert-based assumptions have been formulated and reviewed as described in Section 2.5.

The assumptions described below in Section 2.2 have been defined to tackle these challenges.

2.2 Fundamental assumptions

To meet the need for up-to-date cost estimates despite the key challenges listed in Section 2.1, a few fundamental assumptions were made to perform the analysis. These are listed below, along with a qualitative assessment of their expected influence on the cost results (based on an arbitrary scale including conservative, neutral, optimistic, none, or unknown):

1. **Use of hypothetical reference sites**
   A hypothetical offshore wind farm site has been defined to represent typical conditions expected in future Dutch offshore wind projects. Site attributes have been derived from available data and expert judgment (see Section 2.6).
   Expected influence on results: Neutral. This study provides generic cost estimates that do not belong to any specific site but have been designed to represent the most common site conditions.

2. **Reliance on present knowledge levels**
   Given the unpredictability discussed in key challenge C of Section 2.1, the input assumptions used in this study have been largely based on present knowledge and price levels. Publicly available hindcast weather data for the Dutch North Sea has been used to quantify the weather risk.
   In some instances, however, specialized methods or technologies that are still in a research and development phase and are not yet commercially available at scale have been considered in the analysis (e.g. a vibro-hammer capable of removing extra-large monopiles, an internal cutting tool passing through the minimum diameter section of a monopile and expanding to perform a full diameter cut 6m below seabed, etc.). This has been limited to solutions that have already been validated in relevant environment (i.e. technology readiness level ≥ 5) and have a credible technology development roadmap aligned with the needs of the offshore wind industry.
   Expected influence on results: Neutral, as future price and technology levels are not predictable. While technological advancements are likely to bring costs down, future market dynamics and regulatory changes may drive costs in either direction.

3. **Exclusion of EoL revenues and onshore processing costs**
   All costs associated with the handling and processing of EoL wind farm components onshore (after they reach the port's quays) as well as revenues resulting from the sale of systems/parts/materials to end users have been neglected from the analysis. This assumption is made for the following reasons:
   a. Offshore removal and transport costs are expected to account for ~80% of the total decommissioning costs of an offshore wind farm [3].

b. Considering all offshore wind farm subsystems, over 90% (by mass) of the materials in an offshore wind farm are already recyclable and expected to yield net profits [3].
c. Low maturity of the EoL market brings high uncertainty in its cost structure and expected margins (see challenge D in Section 2.1).

Expected influence on results: Moderately conservative, likely leading to a slight overestimation of the net total cost of decommissioning due to neglecting the moderate overall profits expected from all EoL processes (once components reached the port's quayside).

4. Consideration of a single decommissioning port

This study assumes that all decommissioned subsystems are transported to a single port located approximately 105 km away from the reference site, which is assumed ready to handle all waste flows without requiring project-specific investments in quaysides or infrastructure. These assumptions are justified by:

a. The offshore wind ports nearest to the upcoming sites in the Roadmap 21GW are IJmuiden and Eemshaven, both of which have announced investments or expressed interest in developing offshore wind farm decommissioning services.
b. The selection of a decommissioning port is driven by site-specific, component-specific, and space-related considerations/constraints that cannot be generalized. However, selecting the nearest port reduces transport costs and a single port strategy reduces project complexity so, where possible, developers are likely to prefer this option.
c. Port facilities and offshore wind decommissioning services are expected to be mature by the time that new Roadmap 21GW sites reach the end of their service lives.

Expected influence on results: Moderately optimistic, likely leading to a slight underestimation of total costs.

5. No power production during decommissioning

It is assumed that all turbines cease operation at the start of offshore decommissioning activities. This is justified by:

a. The dependency of production revenues on highly uncertain future offtake prices as well as the highly project-specific decommissioning project schedule (see challenge D in Section 2.1).
b. A decommissioning bank guarantee is supposed to provide security against default and abandonment, including cases where all assets are unfit for production.

Expected influence on results: Moderately conservative, likely leading to a slight overestimation of the net total costs.

6. Single-phase campaigns

The study assumes that each decommissioning campaign is executed in a single continuous phase. In reality, a campaign's schedule will strongly depend on the selected contractor and the schedule of specialized vessels, which are likely to prioritize wind farm installation campaigns due to greater commercial pressures, so it is likely that decommissioning campaigns will be split into multiple phases. However, the number of phases and when they occur is difficult to predict making any other assumption arbitrary.

To ensure that seasonality effects are properly included in the outputs, the simulations are repeated varying the campaign start date throughout all the months of the year (assuming that work starts on the first day of the month). The output metrics presented in Chapter 4 represent the average results of the different starting months and weather years considered. The complete statistical overview can be found in Appendix F.

Expected influence on results: Neutral.

7. **24h operations**
   All offshore campaigns modelled in this study have been considered to run on staggered shifts covering 24h. This is in line with what is expected to occur in reality.
   Expected influence on results: Neutral / optimistic, potentially leading to an underestimation of total costs only in the case of a few offshore activities (e.g. removal of scour protection) that prove challenging to execute during nighttime.

8. **Exclusion of learning curve effects**
   This study neglects the progressive reduction in the duration of repetitive activities characterizing a decommissioning project. This is because:
   a. No reliable data on learning curves for offshore wind decommissioning projects is available.
   b. Input activity duration estimates aim to represent expected values for the whole project.
   Expected influence on results: Neutral.

9. **Exclusion of transmission system decommissioning**
   Costs associated with the removal of high-voltage substations and export cables are excluded, as these are the responsibility of the transmission system operator (TenneT) and are expected to occur separately.
   Expected influence on results: None.

These general assumptions form the foundation of the cost estimation methodology. They are deemed to be balanced overall and are not expected to introduce any important biases in the results of the analysis. Campaign-specific assumptions influencing removal and transport processes have been made too, but they are discussed separately in Section 3.2 and its subsections focusing on each campaign individually.

2.3 Scope of the analysis

Following discussions with KGG, to tackle the uncertainty associated with the upcoming sites in the Roadmap 21GW (which still need to be tendered), it was decided that TNO would consider the removal and transport of the five different scenarios outlined in **Figure 2.1**. The inputs used in the simulations of each scenario are discussed in Chapter 3. The baseline result set is presented in Chapter 4, whereas the results of the other scenarios are reported in the appendices (the results of Scenario A, Scenario B, Variation 1, and Variation 2 are reported in Appendix B, Appendix C, Appendix D, and Appendix E, respectively).

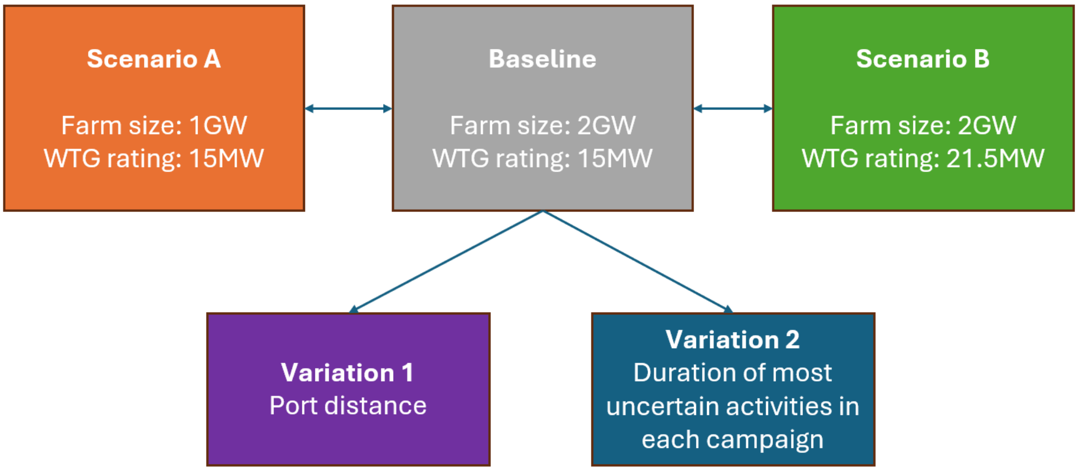

Figure 2.1: Overview of the five different result sets generated.

For each scenario, the costs of the following decommissioning phases have been estimated:
- Pre-decommissioning offshore campaigns (inspections, surveys, turbine preparations);
- Offshore removal, transport, and unloading of:
  1. Wind turbine generators (WTGs);
  2. Inter-array cables (IACs);
  3. Secondary steel components;
  4. Full removal of monopile foundations (MPs);
  5. Partial removal of MPs (6 m below seabed);
  6. Full removal of scour protection layers (SPLs);
- Post-decommissioning offshore campaigns (seabed surveys).

Each removal and transport campaign has been simulated individually to enable evaluation of full and partial removal strategies as requested by KGG.

2.4 Simulation model

TNO’s UWiSE Decommission [13] software has been used to estimate the expected removal and transport costs of the reference offshore wind farm site. UWiSE Decommission is a state-of-the-art software for high-fidelity modelling of offshore wind farm decommissioning campaigns, resulting from over 25 years of research into lowering the cost of offshore wind energy logistics, including installation, operation, maintenance, and decommissioning. The software uses a discrete event simulation algorithm that allows to model dependencies on activity sequences, resources, and weather limits in every simulation. More details on the software and underlying algorithm can be found in [10].

2.5 Input gathering

UWiSE Decommission simulations require three types of input data, including the information described below.

- **Input Excel file**, containing:
  - Reference site characteristics (incl. port and site locations, farm layout, etc.);
  - Asset information (incl. components breakdown);
  - Resources information (incl. vessels and equipment with associated costs).

- **Metocean data table**, containing hourly time series of the following metocean parameters (at the site location):
  - Mean wind speed at tower base [m/s];
  - Mean wind speed at hub height [m/s];
  - Significant wave height [m];
  - Mean current speed at seabed depth [m/s].

- **Method statement descriptions** of every offshore campaign, containing:
  - Activity sequence (e.g. parallel or serial activities, repetitions, etc.);
  - Activity durations [h];
  - Resource dependencies (incl. vessels and equipment involved in every activity);
  - Weather dependencies (incl. operational limits and weather windows).

Hindcast data at the reference site location sourced from the Met Ocean Data Portal [14] has been used to generate the metocean data table. All technical inputs and assumptions used in the preparation of UWiSE Decommission's Excel input file and method statement descriptions have been formulated based on:

- **Review of available data on Roadmap 21GW sites**. Publicly available data on every Dutch offshore wind farm site in the Roadmap 21GW has been searched and analysed, mainly focusing on geophysical and geotechnical site conditions and, where available, historical information regarding the installation of WTGs, IACs, MPs, and SPLs.

- **Review of scientific and grey literature**. More than 70 sources including scientific articles, handbooks, reports, decommissioning plans, and press releases have been reviewed.

- **In-house knowledge from TNO experts.** Relevant TNO intellectual property obtained in previous projects on offshore wind farm decommissioning and/or transport & installation could be leveraged.

- **Feedback from industry stakeholders**. An input validation workshop was held in TNO's office in Den Haag on 24 September 2025. The workshop was attended by 22 participants (3 of which online), including representatives of:

  - Wind farm developers (x5)
  - Offshore contractors (x4)
  - Specialized equipment suppliers (x3)
  - Cable manufacturers (x1)
  - Monopile manufacturers (x1)
  - Offshore engineering companies (x1)
  - Rijkswaterstaat (x1)
  - RVO (x2)
  - KGG (x1)
  - TNO (x3)

  In the workshop, TNO presented its preliminary input assumptions intended for this study and asked for feedback from the attendees. Participants were allowed to provide feedback until 2 October 2025 via (anonymous) surveys or email. A total of 37 feedback forms and 4 emails have been processed and critically reviewed, and the inputs of the analysis have been revised accordingly. This report presents the updated inputs, assumptions, and results after such review.

2.6 Reference sites definition

A hypothetical site representative of upcoming Dutch offshore wind sites in the Roadmap 21GW has been defined for each simulation scenario (Section 2.3). The sites' attributes and characteristics of relevance for a decommissioning project have been determined based on:

- **Processing of official information available on the upcoming Roadmap 21GW sites** (as published on RVO's website [6]). Where possible, relevant attributes —such as the distance from the nearest offshore wind port— have been determined based on capacity-weighted averages of the known attributes of the upcoming sites in the Roadmap 21GW.

- **TNO expert knowledge.** Expert assumptions have been used to determine expected attributes not directly available in the literature such as component sizes and masses, which are needed for vessel selection.

- **Scientific and grey literature.** Publicly available sources have mainly been used to sanity-check TNO's expert assumptions.

- **Feedback from industry stakeholders**. Some attributes of the reference site have been adjusted based on expert feedback received after the input validation workshop (as discussed in Section 2.5).

The reference sites are described in Section 3.1.

3 Inputs

3.1 Reference site conditions

Hypothetical sites with a single offshore substation located ~105 km west of the IJmuiden port, falling approximately between IJmuiden Ver Gamma and the Nederwiek wind farm zone, have been considered for each simulation scenario (Section 2.3). Simple rectangular layouts with equally spaced turbines have been considered, with the number of rows and inter-turbine distances varying according to the corresponding scenario, and reasonable cable layouts defined based on both qualitative and quantitative considerations. Figure 3.1 depicts the sites considered for the Baseline, Scenario A, and Scenario B.

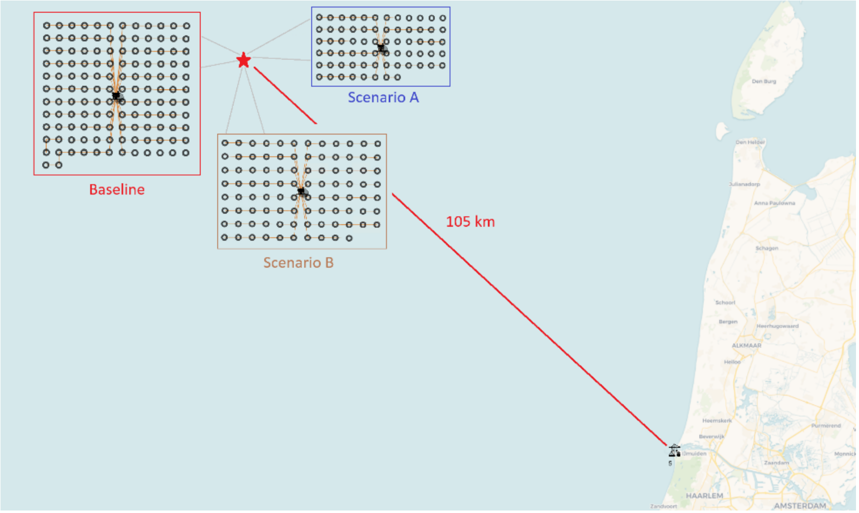

Figure 3.1: Snapshot of the wind farm sites considered in Baseline, Scenario A, and Scenario B.

The key attributes of the reference sites considered for the Baseline, Scenario A, and Scenario B simulations are reported in Appendix A. The same reference site as the Baseline has been used for the Variation 1 & 2 scenarios, except for two increased port distances considered in Variation 1 simulations (~160 km and ~210 km).

Weather variability has been taken into account by repeating each simulation over 40 different weather years. The hourly time series of wind speed (both at 10m and reference hub height), significant wave height, and current speed used in the simulations have been sourced from DHI's official metocean portal developed for RVO [14]. Table 3.1 reports the coordinates of the metocean location considered in all scenarios.

Table 3.1: Metocean location input used in all simulations.

X-coordinate	Y-coordinate	UTM Zone
526955.47	5882708.87	31U

3.2 Assumed removal methods

This section presents the underlying assumptions and method statement descriptions of every modelled offshore campaign, each with its own subsection.

Given the scope of this report, only the list of steps in the simulated method statements and their aggregated duration excluding weather delays (i.e. the sum of all the duration inputs of critical path activities) for the baseline scenario have been reported here. However, for the discrete event simulation, each step has been assigned a duration, weather limits, and where applicable a weather window policy.

3.2.1 Pre-decommissioning campaign

The pre-decommissioning campaign is performed to prepare the offshore wind farm for safe and efficient dismantling. It includes a combination of inspection, surveying, and preparatory activities at each turbine location. The following key assumptions have been applied:

1. The campaign consists of the following parallel activities:
    a. Underwater inspection of foundations, SPL, and cable burial points.
    b. Multibeam echosounder (MBES) surveys of jack-up areas and cable routes.
    c. On-turbine decommissioning preparations, incl. disconnection of internal circuits and hydraulic couplings, removal of fluids, checking and addition of lifting points on turbine, monopile, and secondary steel components, etc.

2. Turbines are assumed to be non-operational at the start of the campaign (i.e. no power production is considered).

3. Vessel port calls occur every 14 days and last 24h.

The following specialized vessels and equipment have been considered for this campaign:

- 1x unmanned surface vehicle (USV) equipped with MBES system;
- 1x remotely operated vehicle (ROV) for subsea inspection;
- 1x service operation vessel (SOV) with walk-to-work (W2W) gangway system for technician access.

Table 3.2 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.2: Simulated method statement of pre-decommissioning campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold red** font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
A1	USV mobilization
A2	USV transits to first WTG (@5 knots)
A3	Positioning
A4	ROV deployment & testing
A5	ROV inspection of foundation, SPL, and cable burying point
A6	Retrieval of ROV
A7	MBES survey of jack-up area survey 400x400 m2
A8	Survey of cable route with DP system on (@3.5knots) till next turbine

ID	Method statement step (set of tasks/activities)
A9	USV transits back to port
A10	USV demobilization
	In parallel
B1	SOV mobilization
B2	SOV transits to first WTG (@8 knots)
B3	SOV transits within wind farm (@5 knots)
B4	Technicians W2W transfer to turbine
B5	**Decommissioning preparations** (incl. turbine de-energization and earthing, unplug cable connections in/from tower & nacelle, remove loose parts, disconnect hydraulic systems, remove oils/fluids and secure against leakage, check lifting points and attach new ones where needed, pre-loosening of bolts where possible, etc.)
B6	Technicians W2W transfer back to SOV
B7	SOV transits back to port (@8 knots)
B8	SOV demobilization

Baseline perfect weather duration: **8.2 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities. USV and SOV campaigns are assumed to happen in parallel.

3.2.2 WTG removal campaign

The wind turbine removal campaign includes the removal and transport of all wind turbine subsystems. The following key assumptions have been applied:

1. Five lift strategy: blades x3; nacelle-hub assembly; tower assembly.
2. Turbine preparations already performed during pre-decommissioning.
3. Dismantling of 21.5MW turbines (Scenario B) requires a larger jack-up vessel (JUV) than the one used in the 15MW turbine scenarios.
4. Shuttle strategy: every 4 turbines the JUV goes back to port to unload WTG components.

The following specialized vessels and equipment have been considered for this campaign:

- 15MW scenarios - 1x JUV with ~1.75 kton crane, similar class as Van Oord's Aeolus [15] with an upgraded crane;
- 21.5MW scenario - 1x JUV with ~3 kton crane, similar class as Van Oord's Boreas [15].

Table 3.3 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.3: Simulated method statement of WTG removal campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold** red font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	JUV mobilization
2	JUV jacks down at port
3	JUV transits to first WTG (@10.5 knots)
4	JUV transits within wind farm (@5 knots)
5	JUV positioning and jacking up
6	Technicians transfer on WTG
7	**Wind turbine blade removal** (x3)
8	**Removal of nacelle-hub assembly**
9	**Removal of tower assembly** (single lift)
10	JUV jacks down
11	JUV transits back to port (@10.5 knots)
12	JUV jacks up at port
13	JUV unloads removed blades at port (in racks of three)
14	JUV unloads removed tower assemblies at port
15	JUV unloads removed nacelle-hub assemblies at port
16	USV demobilization

Baseline perfect weather duration: **34.1 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.3 IAC removal campaign

The inter-array cable removal campaign includes the removal and transport of the buried cable sections running between turbines. The following key assumptions have been applied:

1. IACs are near end-of-life and will not be reused so they do not need to be treated with care.

2. Cables (with their protection system) are cut near the monopile inlet point using a working-class ROV (WROV). A system consisting of a hydraulic gripper and a recovery buoy is used to pull up the first stretch of cable on deck, with assistance from the WROV. The cable protection system (CPS) is removed on the deck from the first portion of the cable.

3. A suitable platform supply vessel (PSV) extracts the buried IAC from the sand by pulling. While retrieving, the cable is cut on deck in ~11m sections allowing those to fall into an open top 40ft container. Once a container is filled (weight limited), it is lifted elsewhere on deck and replaced by an empty one so the operation can continue until the vessel capacity (~58 containers) is reached.
4. Shuttle strategy: the PSV returns to port every ~45 km of IAC removed to unload the containers.

5. Each cable crossing is assumed to add 1 day of work to the total campaign duration and require the use of a controlled flow excavation (CFE) tool.

6. It is assumed that no scour protection is applied to protect IAC other than over cable crossings and around monopiles.

7. The removal of the IAC portion inside each monopile is performed within the secondary steel removal campaign to avoid additional transfers of technicians.

8. The removal of the IAC portion inside the offshore substation is neglected.

The following specialized vessels and equipment have been considered for this campaign:
- 1x PSV equipped with cable cutting and container handling equipment;
- 1x WROV for underwater cutting of cables;
- 1x CFE tool (for cable crossings only).

Table 3.4 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.4: Simulated method statement of IAC removal campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold** red font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	PSV mobilization
2	PSV transits to first WTG location (@10 knots)
3	PSV transits within wind farm (@5 knots)
4	Launching of WROV
5	WROV cuts cable near MP inlet (on extreme end of CPS)
6	WROV attaches hydraulic gripper system to the cable end just cut
7	Retrieval of WROV
8	Pull up of cable end (incl. CPS) on PSV deck using gripper system
9	Removal of CPS on PSV deck
10	**Pull out of IAC between two turbines** (incl. cutting in 11m sections and storage in containers)
11	Launch WROV
12	WROV cuts cable near MP inlet of next turbine
13	Retrieve WROV
14	Pull out last cable section and remove CPS on deck
15	PSV transits back to port
16	Unloading of filled containers, loading of empty ones, and bunkering
17	PSV demobilization

Baseline perfect weather duration: 31.7 h/location (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.4 Secondary steel removal campaign

The secondary steel removal campaign includes the removal and transport of secondary steel components and cable sections running inside the monopiles until the hang-offs. The following key assumptions have been applied:

1. Lifting points on secondary steel are already arranged during the pre-decommissioning campaign so the construction support vessel (CSV) can execute the lifts.
2. Shuttle strategy: the CSV returns to port every 10 locations (8 for the 21.5MW scenario) to unload the removed secondary steel components and IAC portions.

The following specialized vessels and equipment have been considered for this campaign:

- 1x CSV equipped with a ~120ton crane and a W2W gangway.

Table 3.5 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.5: Simulated method statement of secondary steel removal campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold** red font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	CSV mobilization
2	CSV transits to first WTG location (@12 knots)
3	CSV transits within wind farm (@5 knots)
4	Dynamic positioning
5	Technicians transfer on MP access platform
6	Technicians cut cable below hang-off and attach sock and winches for its removal (in parallel: secondary steel removal preparations on deck are started)
7	Retrieval of IAC portion from MP
8	Technicians transfer back on CSV
9	**Removal of MP internal platform**
10	**Removal of main access platform and davit crane**
11	**Removal of boat landings**
12	CSV transits back to port (@12 knots)
13	Unloading of removed components at port
14	CSV demobilization

Baseline perfect weather duration: **13.9 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.5 MP full extraction campaign

The monopile full extraction campaign includes the removal of monopile foundations (without secondary steel, which is removed in a prior campaign) as a whole and their transport to port. The following key assumptions have been applied:

1. **Full removal of extra-large monopile foundations is assumed feasible** in predominantly sandy soil conditions (MP size and relevant soil parameters considered in the different scenarios can be found in Appendix A), using an extra-large vibro-hammer with an eccentric moment of the order of 4,000 kgm. Although this technology is still to be developed and demonstrated at a similar scale, its present TRL level, market potential, and development roadmap make it reasonable to believe that a similar solution will be commercially available at the time of decommissioning. This is in line with the scope of assumption 2 discussed in Section 2.2 and was confirmed by most of the feedback received from industry stakeholders.
   Note: this assumption is strictly linked to the non-cohesive soil conditions considered. For more cohesive soils, e.g. where relatively thick layers of silty clays can be found, vibro-removal is expected to be much more difficult [16]. Industrial research is currently very active in developing alternative or complementary solutions to solve this issue (e.g. [17], [18]). However, given the dominance of sandy soil conditions in the Roadmap 21GW, full monopile removal in highly cohesive soils remains out of the scope of this study. Qualitatively speaking, where feasible, it is expected to be a more complex and costly operation than what has been modelled here.

2. A floating heavy lift vessel (HLV) with a crane capacity of the order of ~4 kton is used for the MP vibro-removal operations. The vessel selection has been sanity-checked via a simple line pull estimate based on static calculations (assuming that soil liquefaction reduces the total friction to 25% of its static value and that no plug is formed at the end of the pile due to its large size [19]). The feedback received from some industry stakeholders also suggested a similar vessel selection.

3. Shuttle strategy: the HLV returns to port to unload every 4 monopiles removed.
   Note: workshop participants could not reach consensus on the preferred logistics strategy, with some stakeholders suggesting that a shuttle strategy may be preferable where other would expect a feeder strategy be used in this campaign. A shuttle strategy has been chosen here due to the complexity of the floating-to-floating lift required to unload the removed pile onto a barge. In fact, so far shuttle strategies have typically been preferred over feeder strategies in installation campaigns executed by HLVs, and given that decommissioning campaigns may be more likely to occur in shoulder seasons (with poorer weather conditions), the risk penalty introduced by the complex lifts is expected to outweigh the benefit of the avoided HLV transits.

4. Scour protection rocks inside (filter layer only) and around (filter and armour layers) the monopile do not affect the execution of the vibro-removal operation.

5. No seabed restoration activities are required after pile removal.

The following specialized vessels and equipment have been considered for this campaign:

- 1x HLV equipped with ≥4 kton crane, dynamic positioning system (at least class 2), and seafastening gear;
- 1x Vibro-lifting tool with up to ~4,000 kgm of excentric moment and 25Hz of excitation frequency;

- 1x Down-ending bucket of adequate size.

Table 3.6 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.6: Simulated method statement of MP full extraction campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold red** font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	HLV mobilization
2	HLV transits to first MP location (@11 knots)
3	HLV transits within wind farm (@5 knots)
4	Dynamic positioning
5	Vibro-hammer & deck preparations
6	Attach vibro-lifting tool to MP
7	Soil liquefaction
8	**MP vibro extraction**
9	MP lifting onto down-ending bucket
10	Down-ending of MP
11	Lift MP from down-ending bucket to seafastening location
12	MP seafastening
13	HLV transits back to port
14	Unloading of removed MPs
15	HLV demobilization

Baseline perfect weather duration: **18.5 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.6 MP cutting campaign

The monopile cutting campaign includes partial removal of monopile foundations (without secondary steel, which is removed in a prior campaign) cut 6m below the seabed and their transport to port. The following key assumptions have been applied:

1. The cut 6m below the seabed is assumed to be performed from the inside of the monopile, using a specialized abrasive waterjet (AWJ) cutting tool consisting of 8 staggered nozzles. The tool is assumed to be capable of fitting into the minimum pile diameter section and then expand its cutting arms (or frame) to cut the pile across a larger diameter section. As for the vibro-hammer, a similar expandable tool is still to be developed. However, given the maturity of AWJ (and/or laser) cutting technology, it is reasonable to believe that similar tools will be commercially available at the time of decommissioning (as per assumption 2 in Section 2.2). **Note:** in case expandable tools prove not to be feasible, a two-cuts strategy would likely be required: an external cut slightly above the seabed first, followed by an internal (or external) cut at target depth. A similar strategy can already be accomplished with existing

technologies (e.g. [20] and [21]), but would require additional work and thereby increase the campaign costs.

2. The internal dredging operation needed to remove sand and filter layer rocks from inside the MP and make enough space for the cutting tool to reach the target depth is assumed to be feasible, despite the challenge posed by the taper of the pile imposing equipment to pass through its minimum diameter section.
   Note: if internal dredging proves unfeasible due to the pile's bottleneck, either a two-cut strategy or an external cutting 6m below the seabed would be required.

3. Before the cut starts, the waterjet tool (potentially without abrasives) may be used to clean the cutting region from residual sediment and/or marine growth.

4. A JUV with a crane capacity of ~1.75 kton (similar to the one used for the 15MW WTG removal) is used in all scenarios. This is to:
   a. Ensure sufficient crane capacity to pull the pile out of the seabed after the cut.
   b. Ensure adequate workability of the cutting operation.

5. Feeder strategy: two feeder barges (each towed by a tug boat) are used to transport the down-ended monopile portions to port so the JUV can work without interruption. Each barge can carry up to 3 cut monopiles.
   Note: workshop participants could not reach consensus on the preferred logistics strategy, with some stakeholders suggesting that a shuttle strategy may be preferable, while others would expect a feeder strategy be used in this campaign. Finally, a feeder strategy has been chosen diversely from the full removal campaign. This is because the dynamic lift's complexity is lower in this case due to the use of a JUV and the reduced size of the cut piles.

6. No seabed restoration activities are required after partial removal (despite the 6m deep excavation pit inside the pile).

The following specialized vessels and equipment have been considered for this campaign:
- 1x JUV equipped with ~1.75 kton crane (same as the one assumed for the 15MW WTG removal);
- 2x Feeder barges capable of carrying 3 cut piles at a time;
- 2x Tug boats (≥5,000 bhp) to tow the barges;
- 1x expandable AWJ cutting tool with 8 nozzles;
- 1x MP extraction & down-ending flange capable of transferring the line pull required to extract the cut pile from the seabed;
- 1x Down-ending bucket of adequate size (on the JUV).

Table 3.7 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.7: Simulated method statement of MP cutting campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold red** font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	JUV, barges, tug boats mobilization
2	JUV jacks down at port
3	JUV transits to first MP location (@10.5 knots)

ID	Method statement step (set of tasks/activities)
4	JUV transits within wind farm (@5 knots)
5	JUV positioning and jacking up
6	Deck preparations of dredging and cutting equipment
7	Dredging tool deployment
8	**Internal dredging operation**
9	Retrieval of dredging tool
10	Deployment of internal AWJ cutting tool
11	Cutting preparation (clean cutting surface with waterjet)
12	**Pile cutting operation**
13	Retrieval of AWJ cutting tool
14	Attach MP lifting and down-ending flange
15	Extraction of cut MP & lifting onto down-ending bucket on JUV
16	Down-ending of cut MP
17	**Dynamic lift of cut MP from down-ending bucket to barge**
18	Seafastening of cut MP
19	Feeder barge is towed back to port
20	Unloading of removed MPs
21	JUV, barges, tugs demobilization

Baseline perfect weather duration: **31.4 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.7 SPL removal campaign

The scour protection removal campaign includes the removal and transport of the scour protection rocks of both filter and armour layers around the removed foundations. The following key assumptions have been applied:

1. Parallel feeder strategy: two grab dredgers work in parallel on two different locations. Each grab dredger is supported by two pairs of connected hopper barges (3,000 m3 capacity per pair) so it can work continuously. Each pair of connected hopper barges is towed by two tugs.

2. Grab dredgers remove both armour and filter layer rocks together. Each grab dredger has been assumed to remove an average of ~130 kton of scour protection rocks per hour (net productivity, after having corrected for sand, water, and organic material also grabbed). Although dredging productivity is expected to reduce significantly in the last stages of SPL removal around foundation areas, a constant productivity rate was modelled. Hence, this should be considered representative of the average productivity of the whole operation.

3. Simulations are based on the complete removal of the total mass of scour protection rocks (armour + filter) in each scenario as reported in Appendix F.

4. An SOV provides accommodation to support 24h operation.

5. Grab dredgers port calls occur every 14 days and last 24h.

The following specialized vessels and equipment have been considered for this campaign:
- 2x grab dredgers (similar to the Heimal R assumed in [3]);
- 8x hopper barges with 1500 m3 capacity each and connected in pairs;
- 8x tug boats (≥5,000 bhp) to tow the hopper barges;
- 1x SOV.

Table 3.8 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.8: Simulated method statement of SPL removal campaign. Steps shown in blue rows are repeated across multiple locations. Steps highlighted in **bold** red font indicate activities for which input durations have been varied in the Variation 2 sensitivity scenario.

ID	Method statement step (set of tasks/activities)
1	Vessels mobilization
2	Grab dredgers transit to locations (@15 knots)
3	Hopper barge couples transit to locations (@5 knots)
4	Positioning of hopper barges next to grab dredgers
5	**SPL removal**
6	Full hopper barge couples transit back to port (@3.5 knots), grab dredgers move to next location
7	Unloading of scour protection rocks
8	Vessels demobilization

Baseline perfect weather duration: **30 h/location** (excl. weather delays). This number has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.2.8 Post-decommissioning campaign

The post-decommissioning campaign need to be performed in case of both partial and full removal. It includes an MBES survey of each turbine location and the IAC routing. The following key assumptions have been applied:

1. A single survey campaign is modelled. Should multiple surveys be performed at regular intervals, the total costs can be estimated by summing individual contributions.

2. Vessel port calls occur every 14 days and last 24h.

The following specialized vessels and equipment have been considered for this campaign:
- 1x unmanned surface vehicle (USV) equipped with MBES system.

Table 3.9 outlines the sequence of steps in the simulated method statement for this campaign.

Table 3.9: Simulated method statement of pre-decommissioning campaign. Steps highlighted in blue are repeated over multiple locations.

ID	Method statement step (set of tasks/activities)
1	USV mobilization
2	USV transits to first WTG (@5 knots)
3	MBES survey of turbine location 400x400 m2
4	Survey of cable route with DP system on (@3.5knots) till next turbine
5	USV transits back to port
6	USV demobilization

Baseline perfect weather duration: 3.6 h/location (excl. weather delays). This figure has been calculated by dividing the total campaign duration, excluding weather dependencies, by the number of turbine locations in the baseline scenario (134). The total duration includes mobilization, unloading at port, and demobilization activities.

3.3 Key cost assumptions

The expected removal and transport costs have been evaluated from an owner's perspective, in line with the purpose of this study. The cost estimates consist of a combination of three cost categories:

1. **Direct variable costs of vessel operations.** These costs have been calculated with UWiSE Decommission (Section 2.4) based on vessel and equipment day rates as presented in Section 3.3.1.
2. **Mobilization & demobilization costs.** These costs have been applied once for each campaign given that single-phase campaigns have been considered (assumption 6, Section 2.2). Section 3.3.2 provides an overview of these costs.
3. **Other costs.** These costs have been considered as fixed percentages of the total campaign costs resulting from the sum of cost categories 1 and 2, and thus added as a post-processing step. An overview of the costs in this category is given in Section 3.3.3.

3.3.1 Assumed day rates

The direct variable costs of vessel operations have been calculated with UWiSE Decommission based on the discrete event simulation of each offshore campaign (incl. weather dependencies), using input-specified day rates for the vessels and equipment involved.

Net all-inclusive day rates have been considered for all vessels, including:
- Vessel, with built-in access equipment & crane(s)
- Crew and contractor's personnel
- Fuel
- Contractor's margin

Table 3.10 provides a complete overview of the assumed day rates for the different vessel types considered in the various offshore campaigns, along with an indication of which removal campaigns used the vessel and an example or characteristic of that vessel class.

Table 3.10: List of vessel day rates assumed in the analysis. Mentioning of specific proprietary vessels is purely indicative and only intended as an example of which vessel class/type/size is considered. All the day rates mentioned below are TNO assumptions.

Vessel	Example/Class	Day rate	Campaigns
HLV	Bokalift 2	400 k€/day	MP full extraction
JUV 21.5MW	Boreas	390 k€/day	21.5MW WTG removal (scenario B)
JUV	Aeolus	250 k€/day	15MW WTG removal MP cutting
CSV	Boka Tiamat	60 k€/day	Secondary steel removal
SOV	Moxie	60 k€/day	Pre-decom preparations SPL removal
Grab Dredger	Heimdal R	40 k€/day	SPL removal
PSV	MV Grace	30 k€/day	IAC removal
USV (incl. MBES)	Blue Essence	30 k€/day	Pre-decom surveying Post-decom surveying
Tug boat	~5000 bhp	15 k€/day	MP cutting SPL removal
Hopper barge	~1500 m3	12.5 k€/day	SPL removal
Barge	~80 m	10 k€/day	MP cutting

Similarly, all-inclusive day rates have been considered for specialized equipment (other than simple steelwork, which has been considered part of mobilization costs), including:

- Equipment and supporting gear
- Consumables (incl. energy)
- Operating personnel
- Contractor’s margin

Table 3.11 provides a complete overview of the assumed day rates for the different equipment types considered in the various offshore campaigns, along with an indication of which removal campaigns used the tool and an example or characteristic of that equipment class.

Table 3.11: List of equipment day rates assumed in the analysis. Mentioning of specific proprietary technology is purely indicative and only intended as an example of which equipment class/type/size is considered. All the day rates mentioned below are TNO assumptions.

Equipment/Tool	Example/Class	Day rate	Campaigns
Vibro-hammer	GIANT 4000	70 k€/day	MP full extraction
AWJ internal cutting tool	8 cutting nozzles	50 k€/day	MP cutting
CFE	T8000	40 k€/day	Cable crossings only
WROV	With IAC cutter	10 k€/day	IAC removal
Down-ending flange	8-10 m diameter MPs	7.5 k€/day	MP cutting
ROV	Subsea inspection	5 k€/day	Pre-decom surveying
Down-ending bucket	8-10 m diameter MPs	5 k€/day	MP full extraction MP cutting

It is underlined that day rates are a strong driver of the output cost estimates. However, not being a buyer of such services, TNO does not have direct access to commercial rates applied in offshore wind contracts so the assumed rates carry uncertainty.

3.3.2 Assumed mob/demob costs

Mobilization and demobilization of specialized vessels and equipment have been modelled as input-specified fixed costs. Having assumed single-phased campaigns (assumption 6, Section 2.2), these costs have been applied once per campaign. Fixed durations associated with mobilization and demobilization have also been specified, and included in the total campaign duration estimates presented in Chapter 4.

As for day rates, all-inclusive costs have been considered for mobilization and demobilization, including:

- Day rates to be paid during the mobilization and demobilization periods.
- Steelworks (e.g. sea-fastening devices) and deck adjustments.
- Working personnel.
- Consumables.

Table 3.12 provides a complete overview of the mobilization and demobilization costs and durations assumed for each vessel. Table 3.13 provides a similar cost overview for each equipment considered. Note that the figures listed in the table are the sum of mobilization and demobilization, and thus they are applied a single time per campaign. The (de)mobilization of specialized equipment has been considered parallel to that of the vessel where the tool is deployed. Therefore, no mobilization duration has been specified for the equipment.

Table 3.12: List of vessel mobilization costs and durations assumed in the analysis. The figures presented are the sum of mobilization and demobilization costs/durations applied (incl. day rates to be paid during mobilization and demobilization periods).

Vessel	Total cost (mob+demob)	Total duration (mob+demob)	Campaigns
HLV	9.2 M€	20 days	MP full extraction
JUV 21.5MW	9.0 M€	20 days	21.5MW WTG removal (scenario B)
JUV	5.75 M€	20 days	15MW WTG removal MP cutting
CSV	390 k€	6 days	Secondary steel removal
SOV	120 k€	2 days	Pre-decom preparations SPL removal
Grab Dredger	80 k€	2 days	SPL removal
PSV	190 k€	6 days	IAC removal
USV (incl. MBES)	120 k€	2 days	Pre-decom surveying Post-decom surveying
Tug boat	20 k€	2 days	MP cutting SPL removal
Hopper barge	20 k€	2 days	SPL removal
Barge	65 k€	6 days	MP cutting

Table 3.13: List of equipment mobilization costs assumed in the analysis. The numbers presented are the sum of mobilization and demobilization costs applied.

Equipment/Tool	Total cost (mob+demob)	Campaigns
Vibro-hammer	200 k€	MP full extraction
AWJ internal cutting tool	100 k€	MP cutting
CFE	100 k€	Cable crossings only
WROV	30 k€	IAC removal
Down-ending flange	30 k€	MP cutting
ROV	20 k€	Pre-decom surveying
Down-ending bucket	24 k€	MP full extraction MP cutting

3.3.3 Other cost assumptions

Additional cost elements have been applied during post processing as a percentage of the total campaign costs of each offshore campaign. These costs aim to address owner's cost elements that are either own expenses or are transferred by the contractor to the asset owner (i.e. potentially included in the removal & transport contract but not a direct result of vessel and equipment utilization). Table 3.14 provides a complete overview of the additional cost elements considered and their assumed share of total campaign costs.

Table 3.14: List of cost elements modelled as a fixed percentage of the total campaign costs.

Cost element	Fixed percentage
Contingency	10.0%
Port services	3.0% (1.5% for pre- and post-decom campaigns)
Marine coordination	1.2%
Owner’s project management	5.0%
Construction All Risk (CAR) insurance	1.8%

4 Results

This chapter summarizes the results of the baseline simulation scenario. Results are organized in sections corresponding to the different removal campaigns (i.e. pre-decommissioning, WTG removal, IAC removal, secondary steel removal, MP extraction, MP cutting, SPL removal, and post-decommissioning).

The results presented in this chapter are the expected value (average) calculated from 40 x 12 simulations. In fact, each simulation has been repeated using metocean data from 40 different weather years and considering 12 different campaign starting dates (one per month of the year) to adequately factor in year-to-year weather variability and seasonality effects. Appendix F contains box plots that provide a complete statistical overview of all simulation results generated.

The cost item “weather” in the cost breakdown of each subsection has been calculated as the difference between the expected campaign cost (from the 480 simulations) and the perfect weather results, i.e. a simulation of the same campaign neglecting all weather dependencies.

4.1 Baseline scenario

The total expected removal and transport costs for the Baseline scenario (see outline in Section 2.3) are:

- **Full removal: 172.5 k€/MW**, incl. pre-decommissioning, WTG removal, IAC removal, secondary steel removal, MP full extraction, SPL removal, one post-decommissioning survey.
- **Partial removal: 110.6 k€/MW**, incl. pre-decommissioning, WTG removal, secondary steel removal, MP cutting, and one post-decommissioning survey.

The following subsections provide more detailed cost breakdowns for each individual removal campaign.

4.1.1 Pre-decommissioning campaign (Baseline outputs)

Table 4.1: Cost breakdown of the pre-decommissioning campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
SOV use	1.3 k€/MW	32.5%
USV use	0.7 k€/MW	16.8%
Mob & Demob (all vessels & equipment)	0.1 k€/MW	3.2%
Weather	1.1 k€/MW	28.1%

Cost Component	Amount	Share
Contingency	0.4 k€/MW	10%
Marine Coordination	0.0 k€/MW	1.2%
Owner’s Project Management	0.2 k€/MW	5%
CAR Insurance Contractor	0.1 k€/MW	1.8%
Port Services	0.1 k€/MW	1.5%

Expected campaign cost: 4.09 k€/MW (sum of all non-rounded cost components above).

Expected campaign duration: 76.2 days (incl. weather delays).

4.1.2 WTG removal campaign (Baseline outputs)

Table 4.2: Cost breakdown of the WTG removal campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
JUV use	21.3 k€/MW	43%
Mob & Demob (all vessels & equipment)	2.9 k€/MW	5.8%
Weather	14.9 k€/MW	30.1%
Contingency	4.9 k€/MW	10%
Marine Coordination	0.6 k€/MW	1.2%
Owner’s Project Management	2.5 k€/MW	5%
CAR Insurance Contractor	0.9 k€/MW	1.8%
Port Services	1.5 k€/MW	3%

Expected campaign cost: 49.37 k€/MW (sum of all non-rounded cost components above).

Expected campaign duration: 308 days (incl. weather delays).

4.1.3 IAC removal campaign (Baseline outputs)

Table 4.3: Cost breakdown of the IAC removal campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
PSV use	2.6 k€/MW	38%
CFE use (cable crossings only)	0.1 k€/MW	1.8%
WROV use	0.9 k€/MW	12.7%
Mob & Demob (all vessels & equipment)	0.2 k€/MW	2.4%
Weather	1.6 k€/MW	24.2%
Contingency	0.7 k€/MW	10%

Cost Component	Amount	Share
Marine Coordination	0.1 k€/MW	1.2%
Owner’s Project Management	0.3 k€/MW	5%
CAR Insurance Contractor	0.1 k€/MW	1.8%
Port Services	0.2 k€/MW	3%

Expected campaign cost: 6.76 k€/MW (sum of all non-rounded cost components above).

Expected campaign duration: 251.9 days (incl. weather delays).

4.1.4 Secondary steel removal campaign (Baseline outputs)

Table 4.4: Cost breakdown of the secondary steel removal campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
CSV use	2.2 k€/MW	58.6%
Mob & Demob (all vessels & equipment)	0.2 k€/MW	5.3%
Weather	0.6 k€/MW	15.1%
Contingency	0.4 k€/MW	10%
Marine Coordination	0.0 k€/MW	1.2%
Owner’s Project Management	0.2 k€/MW	5%
CAR Insurance Contractor	0.1 k€/MW	1.8%
Port Services	0.1 k€/MW	3%

Expected campaign cost: 3.68 k€/MW (sum of all non-rounded cost components above).

Expected campaign duration: 95.5 days (incl. weather delays).

4.1.5 MP full extraction campaign (Baseline outputs)

Table 4.5: Cost breakdown of the MP full extraction campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
HLV use	16.6 k€/MW	41.3%
Down-ending bucket use	0.2 k€/MW	0.5%
Vibro-removal tool use	2.9 k€/MW	7.2%
Mob & Demob (all vessels & equipment)	4.7 k€/MW	11.7%
Weather	7.3 k€/MW	18.2%
Contingency	4.0 k€/MW	10%

Cost Component	Amount	Share
Marine Coordination	0.5 k€/MW	1.2%
Owner’s Project Management	2.0 k€/MW	5%
CAR Insurance Contractor	0.7 k€/MW	1.8%
Port Services	1.2 k€/MW	3%

Expected campaign cost: **40.2 k€/MW** (sum of all non-rounded cost components above).

Expected campaign duration: **132.9 days** (incl. weather delays).

4.1.6 MP cutting campaign (Baseline outputs)

Table 4.6: Cost breakdown of the MP cutting campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
JUV use	19.4 k€/MW	37%
Feeder barges use	1.4 k€/MW	2.6%
Tug boats use	2.1 k€/MW	3.9%
AWJ cutting tool use	3.9 k€/MW	7.4%
Down-ending bucket use	0.4 k€/MW	0.7%
Down-ending flange use	0.6 k€/MW	1.1%
Mob & Demob (all vessels & equipment)	3.0 k€/MW	5.8%
Weather	10.7 k€/MW	20.4%
Contingency	5.2 k€/MW	10%
Marine Coordination	0.6 k€/MW	1.2%
Owner’s Project Management	2.6 k€/MW	5%
CAR Insurance Contractor	0.9 k€/MW	1.8%
Port Services	1.6 k€/MW	3%

Expected campaign cost: **52.42 k€/MW** (sum of all non-rounded cost components above).

Expected campaign duration: **236.9 days** (incl. weather delays).

4.1.7 SPL removal campaign (Baseline outputs)

Table 4.7: Cost breakdown of the SPL removal campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
Grab dredgers use	6.7 k€/MW	9.9%
SOV use	5.0 k€/MW	7.4%

Cost Component	Amount	Share
Tug + hopper sets use	17.4 k€/MW	25.9%
Mob & Demob (all vessels & equipment)	0.3 k€/MW	0.4%
Weather	23.8 k€/MW	35.4%
Contingency	6.7 k€/MW	10%
Marine Coordination	0.8 k€/MW	1.2%
Owner’s Project Management	3.4 k€/MW	5%
CAR Insurance Contractor	1.2 k€/MW	1.8%
Port Services	2.0 k€/MW	3%

Expected campaign cost: **67.39 k€/MW** (sum of all non-rounded cost components above).

Expected campaign duration: **348.9 days** (incl. weather delays).

4.1.8 Post-decommissioning campaign (Baseline outputs)

Table 4.8: Cost breakdown of the post-decommissioning campaign for the Baseline scenario. All the amounts reported here are an expected value from 480 simulations, rounded to the first decimal digit.

Cost Component	Amount	Share
USV use	0.3 k€/MW	32.7%
Mob & Demob (all vessels & equipment)	0.1 k€/MW	6.1%
Weather	0.4 k€/MW	41.7%
Contingency	0.1 k€/MW	10%
Marine Coordination	0.0 k€/MW	1.2%
Owner’s Project Management	0.0 k€/MW	5%
CAR Insurance Contractor	0.0 k€/MW	1.8%
Port Services	0.0 k€/MW	1.5%

Expected campaign cost: **0.98 k€/MW** (sum of all non-rounded cost components above).

Expected campaign duration: **42.7 days** (incl. weather delays).

5 Conclusions & Recommendations

The expected removal and transport costs of the different subsystems of future Dutch offshore wind farms have been estimated using high-fidelity offshore logistic simulations. A hypothetical Dutch offshore wind farm site, representative for future sites in the Roadmap 21GW, has been considered to provide KGG with general estimates that can guide the updating of the decommissioning bank guarantees required in the upcoming wind farm site decisions. Given the current uncertainty in regulatory frameworks and removal requirements, costs and durations of different subsystem removal campaigns have been estimated separately. This provides KGG with an overview of the expected economic impact of the removal and transport of each individual subsystem so that the amounts of the bank guarantees may be tailored to whatever decommissioning scope will be prescribed in future permits or regulations.

5.1 Key findings

The following key findings have emerged:

- The expected costs of complete removal are estimated approximately at:
  - **172.5 k€/MW** for a 2 GW offshore wind farm featuring 15 MW turbines.
  - **191.1 k€/MW** for a 1 GW offshore wind farm featuring 15 MW turbines.
  - **152 k€/MW** for a 2 GW offshore wind farm featuring 21.5 MW turbines.

  This confirms that:
  - The amount of decommissioning bank guarantees should be updated in case full removal remains the default approach.
  - Scale effects have a significant impact on the expected decommissioning costs (per MW), hence the decommissioning bank guarantees may need to be tailored to the site's grid connection size and turbine rating.

- **Complete removal of scour protection is a major cost driver**. The removal of scour protection layers is found to be the largest contributor to full removal costs, accounting for nearly 40% of the total in the Baseline scenario. This is mainly due to:
  - The rate at which SPL rocks can be retrieved from the seabed of that depth is slow and reduces progressively as the first rocks are removed (then excavation efficiency reduces due to increasing amounts of sediment being grabbed along with filter layer rocks).
  - The lack of specialized vessels for far-offshore SPL removal operations (existing hopper barges have limited seakeeping ability making their use far offshore prone to weather delays).

- **Full vs partial removal of monopile foundations.** If the development and upscaling of vibro-lifting technology continues successfully, monopile full extraction in sandy seabed is found to be more cost-competitive than cutting the piles 6m below the seabed (20-25% lower cost depending on the scenario). However, partial removal may be required for monopiles installed in locations dominated by highly cohesive soils (e.g. clays) and might benefit from significant cost reduction if innovative ways to decouple the cutting campaign from the heavy-lifting activities are found so that a cheaper vessel can be used for cutting.

- **IAC removal has a moderate influence on total decommissioning costs**. IAC removal accounts for less than 5% of the total costs of full removal, provided that cables are buried in sandy sediment and do not need to be reused after removal (thereby not needing a CLV for the removal operations). Early decommissioning cases excluded, IAC reuse is anyhow unlikely as modern IAC cables are certified for 40 years of operation, leaving little residual life at the end of a modern wind farm's lifetime.

- **Port distance influence** (Appendix D). Doubling the port distance from 105 km to 210 km results in a ~12% increase in full removal costs, with SPL removal and MP extraction campaigns being most affected.

- **Activity duration sensitivity** (Appendix E). Campaign costs are highly sensitive to uncertain activity durations. Pessimistic assumptions can increase costs by up to 45%, while optimistic ones can reduce them by 15–35%. Such a large scatter is a direct result of the limited market experience, and is expected to reduce drastically as the first utility-scale decommissioning projects are executed.

- **Weather sensitivity** (Appendix F**)**. Weather-induced delays are a major cost factor accounting for 15-40% (depending on the campaign) of the average removal costs. Year-to-year variability and seasonal effects have been quantified (Appendix F) for each campaign and scenario considered.

5.2 Key limitations

While the study provides robust estimates, several limitations must be acknowledged:

- **High sensitivity to day rates**. Vessel and equipment day rates are a major cost driver, yet they are based on expert assumptions due to limited public data. Even though the input cost assumptions have been partially validated by industry stakeholders participating in the workshop, rates often remain commercially sensitive and confidential information.

- **Site-specific conditions**. Decommissioning costs are highly dependent on site-specific attributes such as soil type, metocean conditions, and infrastructure proximity. The use of hypothetical reference sites provides a reasonable approximation of the average values for the Roadmap 21GW. However, no one size fits all, and ad-hoc simulations would be required to get a more accurate assessment of the decommissioning costs of individual sites, especially where critical conditions deviate from those assumed in this study.

- **Limited real-world experience**. Offshore wind decommissioning is still in its infancy. Many assumptions, especially regarding removal methods and durations, are based on expert judgment and lack large-scale validation, resulting in high uncertainty.

- **No optimization of method statements**. The simulated campaigns reflect realistic but non-optimized logistic scenarios. Future work could explore schedule optimization and inter-campaign synergies, especially for cost-critical and uncertain campaigns such as SPL removal and MP cutting.

- **Exclusion of Transmission System Costs**. Costs related to the decommissioning of export cables and substations are excluded, as they fall under the transmission system operator’s responsibility in the Netherlands.

- **No end-of-life costs and revenues considered.** The costs of handling and processing EoL components onshore and the revenues generated from material resale or reuse are excluded. Overall, this is expected to be moderately conservative estimate but EoL profit margins are highly dependent on the individual campaigns considered and the associated EoL route selected.

- **Ecological, environmental, and social aspects neglected.** The present study only considered the techno-economic aspects of removal and transport of different offshore wind farm subsystems. However, the social, environmental, and ecological implications of different removal strategies should be thoroughly assessed and taken into account when defining offshore wind farm decommissioning provisions.

5.3 Recommendations

To ensure robust and future-proof decommissioning provisions in upcoming Wind Farm Site Decisions (WFSDs), the following recommendations are made:

A. **Use these results to set WFSD bank guarantee provisions but allow flexibility to adjust the amounts during the permit period**. Wind farm owners should be given the chance to propose adjustments to the monetary amounts secured in the decommissioning bank guarantees during the permit period, ensuring that the guaranteed amounts can be reduced in case of favourable market or technological developments. This would spare unnecessary costs for the wind farm owner and thereby (slightly) improve the farm’s profitability. Obviously, adjustment requests should be adequately motivated and supported by evidence and, where in doubt, KGG may ask for independent reviewers to support in their evaluation. More complex is the case where market, technology, or regulatory developments tend to increase the expected costs of decommissioning during the permit period. This risk should also be taken into account in the definition of bank guarantee provisions, but that goes beyond the scope of this assignment.

B. **Adjust estimates in case of complex sites.** WFSDs should allow flexibility for deviations from the average cost estimates proposed here if justified by site-specific conditions or validated cost models. Moreover, for sites in which soil and/or metocean conditions deviate significantly from those considered in this study, or where larger turbine ratings may be expected, it is recommended that the present estimates are updated based on a site-specific assessment.

C. **Encourage data sharing**. As the first decommissioning projects are executed, developers and contractors should be encouraged to share decommissioning data and experience to reduce uncertainty and foster the development and deployment of innovation as the market matures.

D. **Invest in research & innovation around offshore wind farm decommissioning and EoL**. Due to the low market maturity and the commercial opportunity that worldwide offshore wind farm decommissioning projects can be for the Dutch industry, there is a strong need and opportunity for public investments to stimulate research and innovation

(R&I) around offshore wind EoL. The next paragraph lists a few priorities arising from this study.

5.4 R&I priorities

Based upon the largest cost drivers, the following R&I priorities are identified to address the key uncertainties in offshore wind farm removal and transport and bring down costs:

- **Development and upscaling of full monopile removal technologies**. Focus on upscaling and demonstration of existing extraction technology for sandy soils, as well as development and validation of innovative tools and methods for monopile extraction in more cohesive soil conditions.
- **Development and optimization of monopile cutting methods and technologies.** Focus on increasing cutting speed, development and demonstration of flexible equipment for dredging (to reach target cutting depth) and cutting, as well as alternative logistic strategies to reduce costs and emission footprint of partial removal campaigns.
- **Investigation of alternative scour protection removal solutions and technologies**. Focus on more efficient vessels and equipment for deep-water, far-offshore seabed dredging operations, as well as alternative solutions or uses for the removed rocks.
- **Optimization of wind turbine removal operations**. Focus on investigating methods for faster and safer decommissioning preparations and dismantling operations.
- **Integrated campaign optimization & market synergies**. Explore multi-phase and multi-component campaign optimization to reduce overall project costs and durations, as well as potential synergies with nearby construction or maintenance campaigns.

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Appendix A

Reference site conditions

The following tables contain the critical attributes of the reference wind farm sites considered in the different simulation scenarios.

General	**Baseline**	**Scenario A**	**Scenario B**	**Unit**	**Comment**
Port distance	105	105	105	km	From IJmuiden port
Water depth	25.6-37.8	25.6-37.8	25.6-37.8	m	below LAT
UTM Zone	31U	31U	31U	-	-
UTM Easting	526955.47	526955.47	526955.47	m	-
UTM Northing	5882708.87	5882708.87	5882708.87	m	-
Weather data from	MOOD	MOOD	MOOD	-	Metocean location determined by coordinates above (wind farm center)
Soil conditions	**Medium-dense to dense sand,** with some gravel and minor layers of silty clay	**Medium-dense to dense sand,** with some gravel and minor layers of silty clay	**Medium-dense to dense sand,** with some gravel and minor layers of silty clay	-	-
Soil skin friction multiplier “β” (for MP extraction)	0.25	0.25	0.25	-	-
Soil limit skin friction "f_lim" (for MP extraction)	65	65	65	kPa	-

Farm	**Baseline**	**Scenario A**	**Scenario B**	**Unit**	**Comment**
Grid connection size	2000	1000	2000	MW	-
Turbine rating	15	15	21.5	MW	-
Number of turbines	134	68	94	-	-

Turbine spacing factor	5.5	5.5	5.5	-	Multiplier of rotor diameter
Distance between turbines	1298	1298	1518	m	-
Farm surface area	187	86	173	km2	-

WTGs	**Baseline**	**Scenario A**	**Scenario B**	**Unit**	**Comment**
Model	Vestas V236-15.0 MW™	Vestas V236-15.0 MW™	Siemens Gamesa SG 21-276 DD	-	Just as an example of a 21.5MW class turbine
Rotor diameter	236	236	276	m	-
Blade length	115.5	115.5	135	m	-
Blade mass	63.5	63.5	70	ton	-
Tower height	128.25	128.25	150	m	-
Tower diameter	8 to 5.6 (tapered)	8 to 5.6 (tapered)	10 to 7 (tapered)	m	-
Tower-MP attachment type	Bolted	Bolted	Bolted	-	-
Tower mass	870.5	870.5	1000	ton	-
Nacelle-hub length	27.5	27.5	30	m	-
Nacelle-hub width	14	14	15	m	-
Nacelle-hub height	10.7	10.7	12	m	-
Nacelle-hub mass	630	630	1000	ton	-

Foundations	**Baseline**	**Scenario A**	**Scenario B**	**Unit**	**Comment**
Type	TP-less Monopile	TP-less Monopile	TP-less Monopile	-	-
MP length	90	90	90	m	-
MP diameter	8.5	8.5	9.2	m	-
MP mass	1500	1500	2000	ton	-
MP penetration	32	32	32	m	-
Secondary steel mass	125	125	150	ton	-

IACs	Baseline	Scenario A	Scenario B	Unit	Comment
Voltage level	66	66	66	kV	-
Total IAC length	300	152	240	km	-
Number of cables	134	68	94	-	-
IAC cross section diameter (farm average)	150	150	175	mm	-
Burial depth	1.5	1.5	1.5	m	-
Cable unit mass (farm average)	40	40	45	kg/m	-
Cable crossings	5	3	4	-	-

Scour Protection	Baseline	Scenario A	Scenario B	Unit	Comment
Armour layer rock diameter ratio (Darmour/Dmp)	3.5	3.5	3.5	-	-
Armour layer rock diameter (only outside the MP)	29.75	29.75	32.2	m	-
Armour layer height	1.5	1.5	1.5	m	-
Armour layer rock grading	90-250	90-250	90-250	mm	Offshore sieved grading (OSG)
Armour layer Particle density of rocks	2650	2650	2650	kg/m3	-
Armour layer total volume per pile	1149	1149	1346	m3	-
Armour layer total mass whole farm	408	207	335	kton	-

Filter layer rock diameter ratio (Dfilter/Dmp)	5	5	5	-	-
Filter layer rock diameter (partially inside MP)	42.5	42.5	46	m	-
Filter layer height	0.75	0.75	0.75	m	-
Filter layer rock grading	22-125	22-125	22-125	mm	OSG
Filter layer Particle density of rocks	3050	3050	3050	kg/m3	-
Filter layer total volume per pile	1277	1277	1496	m3	-
Filter layer total mass whole farm	522	265	429	kton	-

Appendix B

Smaller Farm Size Results (Scenario A)

The numbers presented in this Appendix are the expected value (average) calculated from 40 x 12 simulations. In fact, each simulation has been repeated using metocean data from 40 different weather years and considering 12 different campaign starting dates (one per month of the year) to adequately factor in year-to-year weather variability and seasonality effects. Appendix F contains box plots that provide a complete statistical overview of all simulation results generated.

The total expected removal and transport costs for Scenario A (see outline in Section 2.3) are:

- **Full removal:** **191.1 k€/MW** (+11% than Baseline), incl. pre-decommissioning, WTG removal, IAC removal, secondary steel removal, MP full extraction, SPL removal, and one post-decommissioning survey.
- **Partial removal:** **123.6 k€/MW** (+12% than Baseline), incl. pre-decommissioning, WTG removal, secondary steel removal, MP cutting, and one post-decommissioning survey.

The following subsections provide the expected cost and duration of each removal campaign.

B.1 Pre-decommissioning campaign

Expected campaign cost: **4.48 k€/MW**, +9% than Baseline.

Expected campaign duration: **41.7 days** (incl. weather delays), -45% than Baseline.

B.2 WTG removal campaign

Expected campaign cost: **55.13 k€/MW**, +12% than Baseline.

Expected campaign duration: **170.2 days** (incl. weather delays), -45% than Baseline.

B.3 IAC removal campaign

Expected campaign cost: **7.04 k€/MW**, +4% than Baseline.

Expected campaign duration: **128.2 days** (incl. weather delays), -49% than Baseline.

B.4 Secondary steel removal campaign

Expected campaign cost: **4.03 k€/MW**, +9% than Baseline.

Expected campaign duration: **51.5 days** (incl. weather delays), -46% than Baseline.

B.5 MP full extraction

Expected campaign cost: **47.23 k€/MW**, +17% than Baseline.

Expected campaign duration: **77.7 days** (incl. weather delays), -42% than Baseline.

B.6 MP cutting campaign

Expected campaign cost: **58.87 k€/MW**, +12% than Baseline.

Expected campaign duration: **134 days** (incl. weather delays), -43% than Baseline.

B.7 SPL removal campaign

Expected campaign cost: **72.1 k€/MW**, +7% than Baseline.

Expected campaign duration: **188.2 days** (incl. weather delays), -46% than Baseline.

B.8 Post-decommissioning campaign

Expected campaign cost: **1.13 k€/MW**, +16% than Baseline.

Expected campaign duration: **23.6 days** (incl. weather delays), -45% than Baseline.

Appendix C

Larger Turbine Rating Results (Scenario B)

The numbers presented in this appendix are the expected value (average) calculated from 40 x 12 simulations. In fact, each simulation has been repeated using metocean data from 40 different weather years and considering 12 different campaign starting dates (one per month of the year) to adequately factor in year-to-year weather variability and seasonality effects. Appendix F contains box plots that provide a complete statistical overview of all simulation results generated.

The total expected removal and transport costs for Scenario B (see outline in Section 2.3) are:

- **Full removal:** **152 k€/MW** (-12% than Baseline), incl. pre-decommissioning, WTG removal, IAC removal, secondary steel removal, MP full extraction, SPL removal, and one post-decommissioning survey.
- **Partial removal:** **103.3 k€/MW** (-7% than Baseline), incl. pre-decommissioning, WTG removal, secondary steel removal, MP cutting, and one post-decommissioning survey.

The following subsections provide the expected cost and duration of each removal campaign.

C.1 Pre-decommissioning campaign results

Expected campaign cost: **3 k€/MW**, -27% than Baseline.

Expected campaign duration: **56.1 days** (incl. weather delays), -26% than Baseline.

C.2 WTG removal campaign results

Expected campaign cost: **56.22 k€/MW**, +14% than Baseline (due to more expensive vessel).

Expected campaign duration: **223.7 days** (incl. weather delays), -27% than Baseline.

C.3 IAC removal campaign results

Expected campaign cost: **5.36 k€/MW**, -21% than Baseline.

Expected campaign duration: **197.3 days** (incl. weather delays), -22% than Baseline.

C.4 Secondary steel removal campaign results

Expected campaign cost: **2.68 k€/MW**, -27% than Baseline.

Expected campaign duration: **69.2 days** (incl. weather delays), -28% than Baseline.

C.5 MP full extraction campaign results

Expected campaign cost: **30.35 k€/MW**, -24% than Baseline.

Expected campaign duration: **100.1 days** (incl. weather delays), -25% than Baseline.

C.6 MP cutting campaign results

Expected campaign cost: **40.7 k€/MW**, -22% than Baseline.

Expected campaign duration: **184.8 days** (incl. weather delays), -22% than Baseline.

C.7 SPL removal campaign results

Expected campaign cost: **53.6 k€/MW**, -20% than Baseline.

Expected campaign duration: **282.4 days** (incl. weather delays), -19% than Baseline.

C.8 Post-decommissioning campaign results

Expected campaign cost: **0.75 k€/MW**, -24% than Baseline.

Expected campaign duration: **31.9 days** (incl. weather delays), -25% than Baseline.

Appendix D

Port Distance Sensitivity Results (Variation 1)

Variation 1 scenario has been devised to investigate the influence of the port distance on the Baseline cost estimates. This is because it is likely that different ports located further away from the wind farm site may be involved in the decommissioning project. For new sites in the Roadmap 21GW, it is possible that ports from other parts of the Netherlands or in neighbouring countries like Belgium, UK, or Germany (depending on the site) may be used. Therefore, two cases have been considered within Variation 1, one with a port distance increased by a factor of 1.5 (~160 km) and one with an increase of a factor of 2 (210 km) compared to the Baseline scenario. This appendix presents the results of these two cases.

The numbers here are the expected value (average) calculated from 40 x 12 simulations. In fact, each simulation has been repeated using metocean data from 40 different weather years and considering 12 different campaign starting dates (one per month of the year) to adequately factor in year-to-year weather variability and seasonality effects. Appendix F contains box plots that provide a complete statistical overview of all simulation results generated.

The total expected removal and transport costs for the largest distance considered in Variation 1 (~210 km) are:

- **Full removal (160 km port distance): 181.6 k€/MW** (+5% than Baseline), incl. pre-decommissioning, WTG removal, IAC removal, secondary steel removal, MP full extraction, SPL removal, and one post-decommissioning survey.
- **Full removal (210 km port distance): 193.3 k€/MW** (+12% than Baseline).

- **Partial removal (160 km port distance): 113.2 k€/MW** (+4% than Baseline), incl. pre-decommissioning, WTG removal, secondary steel removal, MP cutting, and one post-decommissioning survey.
- **Partial removal (210 km port distance): 115.3 k€/MW** (+4% than Baseline)

The following subsections provide the expected cost and duration of each removal campaign for the two cases considered in Variation 1.

D.1 Pre-decommissioning campaign results

Port distance increased by a factor of 1.5 (~160 km)
- Expected campaign cost: 4.11 k€/MW, +0.5% than Baseline.
- Expected campaign duration: 76.7 days (incl. weather delays), +0.7% than Baseline.

Port distance increased by a factor of 2 (~210 km)
- Expected campaign cost: 4.13 k€/MW, +1% than Baseline.
- Expected campaign duration: 77.2 days (incl. weather delays), +1.3% than Baseline.

D.2 WTG removal campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 51.1 k€/MW, +3.5% than Baseline.
- Expected campaign duration: 318.9 days (incl. weather delays), +3.5% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 52.57 k€/MW, +6.5% than Baseline.
- Expected campaign duration: 328.2 days (incl. weather delays), +6.6% than Baseline.

D.3 IAC removal campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 6.81 k€/MW, +0.9% than Baseline.
- Expected campaign duration: 254 days (incl. weather delays), +0.9% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 6.87 k€/MW, +1.7% than Baseline.
- Expected campaign duration: 256 days (incl. weather delays), +1.6% than Baseline.

D.4 Secondary steel removal campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 3.8 k€/MW, +3% than Baseline.
- Expected campaign duration: 98.5 days (incl. weather delays), +3.1% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 3.91 k€/MW, +6.2% than Baseline.
- Expected campaign duration: 101.5 days (incl. weather delays), +6.3% than Baseline.

D.5 MP full extraction campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 42.62 k€/MW, +6% than Baseline.
- Expected campaign duration: 140.9 days (incl. weather delays), +6% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 45.08 k€/MW, +12.1% than Baseline.
- Expected campaign duration: 149.1 days (incl. weather delays), +12.2% than Baseline.

D.6 MP cutting campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 53.19 k€/MW, +1.5% than Baseline.
- Expected campaign duration: 237.7 days (incl. weather delays), +0.4% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 53.7 k€/MW, +2.4% than Baseline.
- Expected campaign duration: 238.8 days (incl. weather delays), +0.8% than Baseline.

D.7 SPL removal campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 72.12 k€/MW, +7% than Baseline.
- Expected campaign duration: 363 days (incl. weather delays), +4% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 79.69 k€/MW, +18.3% than Baseline.
- Expected campaign duration: 394.7 days (incl. weather delays), +13.1% than Baseline.

D.8 Post-decommissioning campaign results

Port distance increased by a factor of 1.5 (~160 km)

- Expected campaign cost: 0.99 k€/MW, +1.3% than Baseline.
- Expected campaign duration: 43.3 days (incl. weather delays), +1.3% than Baseline.

Port distance increased by a factor of 2 (~210 km)

- Expected campaign cost: 1 k€/MW, +2.3% than Baseline.
- Expected campaign duration: 43.7 days (incl. weather delays), +2.5% than Baseline.

Appendix E

Activity Duration Sensitivity Results (Variation 2)

Variation 2 scenario has been devised to investigate the influence of the assumed durations of highly uncertain activities on the Baseline cost estimates. To do this, two cases have been considered within Variation 2, one with more pessimistic activity duration estimates than the Baseline and the other with more optimistic ones. The pessimistic scenario has been intentionally designed to be a "worst case". This appendix presents the results of these two cases.

Given that different removal campaigns have different activities whose estimated durations are subject to different uncertainty levels, the changes applied to the baseline duration estimates vary per campaign reflecting TNO assumptions based on internal discussions. The following sections provide a complete overview of all duration changes applied in each campaign and the resulting effect on expected campaign costs and duration.

The numbers reported below are the expected value (average) calculated from 40 x 12 simulations. In fact, each simulation has been repeated using metocean data from 40 different weather years and considering 12 different campaign starting dates (one per month of the year) to adequately factor in year-to-year weather variability and seasonality effects. Appendix F contains box plots that provide a complete statistical overview of all simulation results generated.

E.1 Pre-decommissioning campaign results

Table E.1: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
B5 Decommissioning preparations Baseline: 6 h	Pessimistic	2	12 h
	Optimistic	0.75	4.5 h

Pessimistic case:

- Expected campaign cost: 5.91 k€/MW, +44.4% than Baseline.
- Expected campaign duration: 105.6 days (incl. weather delays), +38.6% than Baseline.

Optimistic case:

- Expected campaign cost: 3.65 k€/MW, -10.7% than Baseline.
- Expected campaign duration: 75.6 days (incl. weather delays), -0.8% than Baseline.

E.2 WTG removal campaign results

Table E.2: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
#7 Wind turbine blade removal (x3) Baseline: 3 h/blade	Pessimistic	1.5	4.5 h/blade
	Optimistic	0.75	2.25 h/blade
#8 Removal of nacelle-hub assembly (one lift) Baseline: 4 h	Pessimistic	1.5	6 h
	Optimistic	0.75	3 h
#9 Removal of tower assembly (one lift) Baseline: 4 h	Pessimistic	1.5	6 h
	Optimistic	0.75	3 h

Pessimistic case:
- Expected campaign cost: 72.84 k€/MW, +47.5% than Baseline.
- Expected campaign duration: 456.3 days (incl. weather delays), +48.2% than Baseline.

Optimistic case:
- Expected campaign cost: 40.31 k€/MW, -18.4% than Baseline.
- Expected campaign duration: 250.7 days (incl. weather delays), -18.6% than Baseline.

E.3 IAC removal campaign results

Table E.3: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New speed
#10 Pull out of IAC between two turbines (incl. cutting in 11m sections and storage in containers) Baseline: 132 m/h	Pessimistic	2/3	88 m/h
	Optimistic	4/3	176 m/h

Pessimistic case:
- Expected campaign cost: 8.61 k€/MW, +27.4% than Baseline.
- Expected campaign duration: 323.3 days (incl. weather delays), +28.4% than Baseline.

Optimistic case:
- Expected campaign cost: 5.88 k€/MW, -13.0% than Baseline.
- Expected campaign duration: 217.5 days (incl. weather delays), -13.6% than Baseline.

E.4 Secondary steel removal campaign results

Table E.4: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
#9 Removal of MP internal platform Baseline: 1 h	Pessimistic	2	2 h
	Optimistic	0.75	0.75 h
#10 Removal of main access platform and davit crane Baseline: 3 h	Pessimistic	2	6 h
	Optimistic	0.75	2.25 h
#11 Removal of boat landings Baseline: 2 h	Pessimistic	2	4 h
	Optimistic	0.75	1.5 h

Pessimistic case:
- Expected campaign cost: 5.23 k€/MW, +41.8% than Baseline.
- Expected campaign duration: 136.1 days (incl. weather delays), +42.5% than Baseline.

Optimistic case:
- Expected campaign cost: 3.3 k€/MW, -10.5% than Baseline.
- Expected campaign duration: 85.3 days (incl. weather delays), -10.7% than Baseline.

E.5 MP full extraction campaign results

Table E.5: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
#8 MP vibro extraction Baseline: 1.5 h	Pessimistic	3	4.5 h
	Optimistic	1/3	0.5 h

Pessimistic case:
- Expected campaign cost: 48.36 k€/MW, +20.3% than Baseline.
- Expected campaign duration: 160 days (incl. weather delays), +20.4% than Baseline.

Optimistic case:
- Expected campaign cost: 37.47 k€/MW, -6.8% than Baseline.
- Expected campaign duration: 123.8 days (incl. weather delays), -6.8% than Baseline.

E.6 MP cutting campaign results

Table E.6: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
#8 Internal dredging operation Baseline: 6 h	Pessimistic	2	12 h
	Optimistic	0.5	3 h
#12 Pile cutting operation Baseline: 10 h	Pessimistic	1.5	15 h
	Optimistic	0.75	7.5 h
#17 Dynamic lift of cut MP from down-ending bucket to barge Baseline: 1 h	Pessimistic	3	3 h
	Optimistic	0.75	0.75 h

Pessimistic case:
- Expected campaign cost: 74.75 k€/MW, +42.6% than Baseline.
- Expected campaign duration: 341.4 days (incl. weather delays), +44.1% than Baseline.

Optimistic case:
- Expected campaign cost: 44.07 k€/MW, -15.9% than Baseline.
- Expected campaign duration: 197.8 days (incl. weather delays), -16.5% than Baseline.

E.7 SPL removal campaign results

Table E.7: List of baseline activity duration changes applied in the optimistic and pessimistic case of the Variation 2 scenario. Activity IDs are taken from the method statement outlined in Section 3.2.1.

Activity	Case	Change factor	New duration
#5 SPL removal Baseline: 52 h	Pessimistic	1.25	65 h
	Optimistic	0.5	26 h

Pessimistic case:
- Expected campaign cost: 82.77 k€/MW, +22.8% than Baseline.
- Expected campaign duration: 441 days (incl. weather delays), +26.4% than Baseline.

Optimistic case:
- Expected campaign cost: 42.33 k€/MW, -37.2% than Baseline.
- Expected campaign duration: 208.9 days (incl. weather delays), -40.1% than Baseline.

E.8 Post-decommissioning campaign results

No critical and highly uncertain activity has been identified in the method statement of Section 3.2.1 so no changes have been applied with respect to the Baseline scenario.

Appendix F
Weather-induced Variability

This appendix provides the statistical overview of the results of the 40 x 12 simulations performed for the different scenarios. The overview is provided via box plots for different campaigns, different campaign starting months, and 40 year of hindcast metocean data.

F.1 Baseline scenario

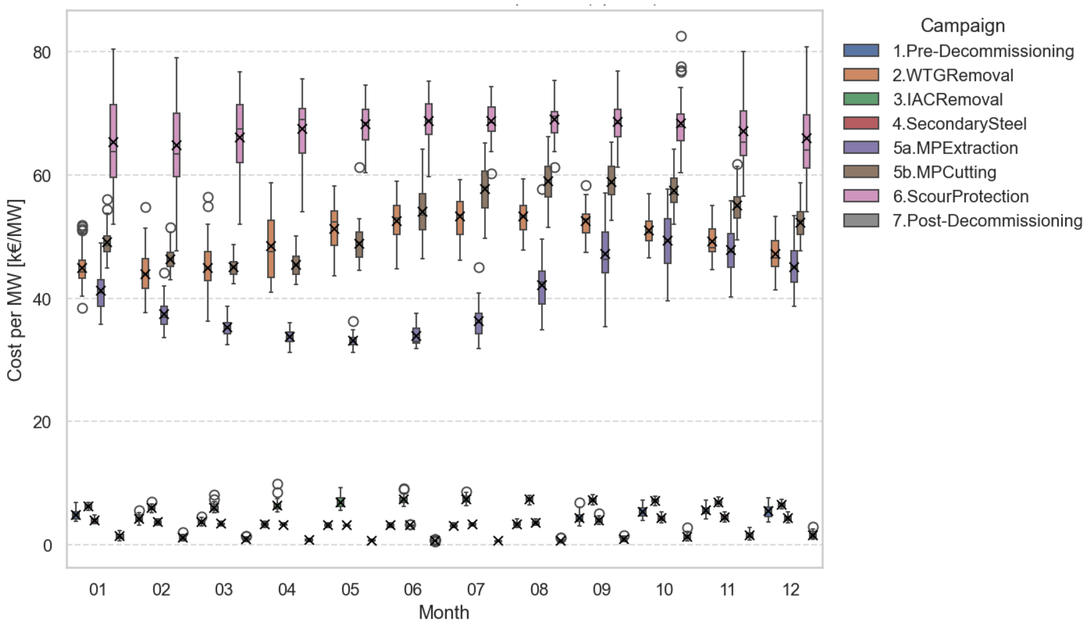

Figure F.1: Distribution of Baseline costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.2 Scenario A (smaller farm size)

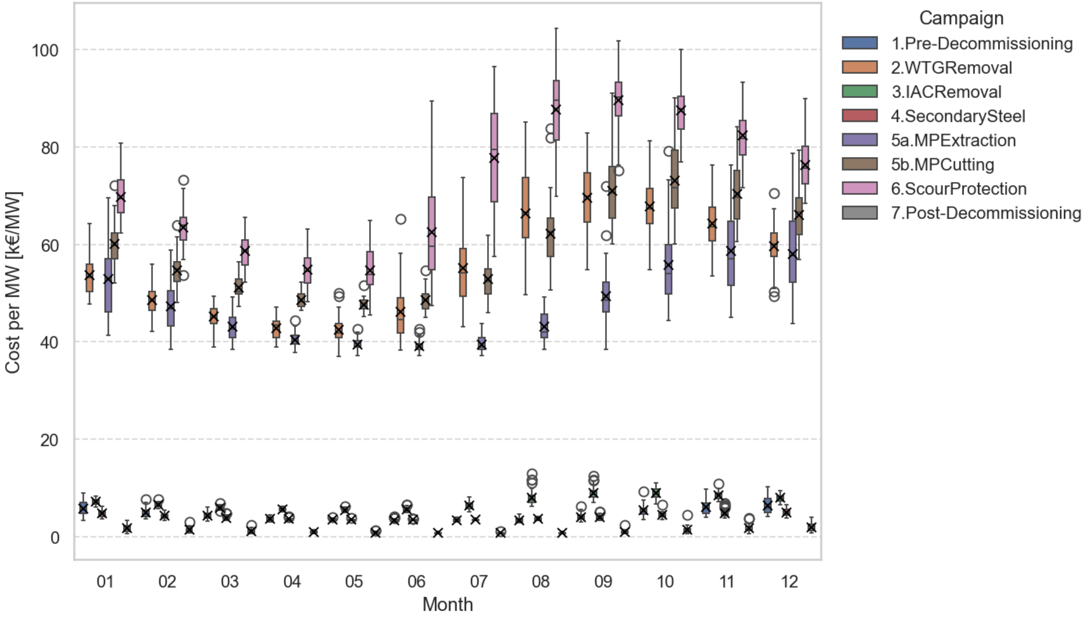

Figure F.2: Distribution of Scenario A costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.3 Scenario B (larger WTG rating)

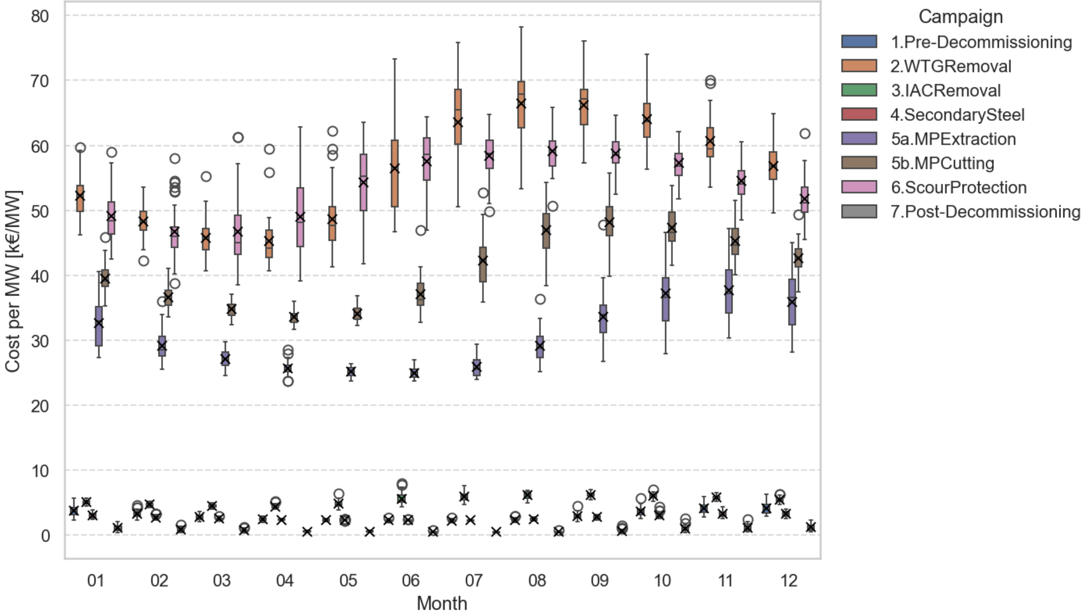

Figure F.3: Distribution of Scenario B costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.4 Variation 1 (port distance 160 km)

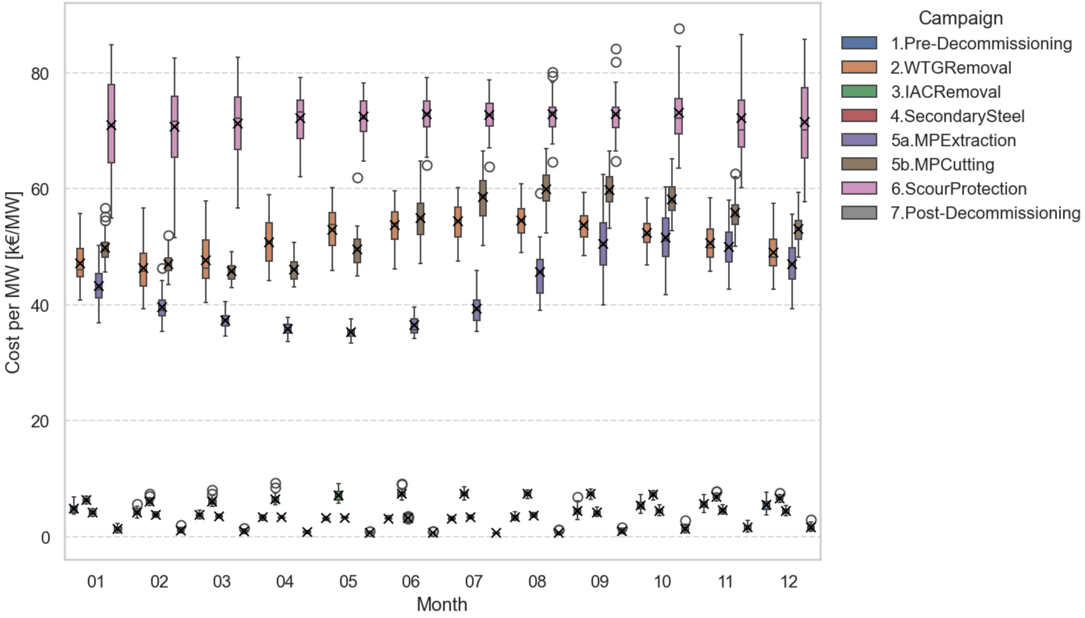

Figure F.4: Distribution of Variation 1 -160km- costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.5 Variation 1 (port distance 210 km)

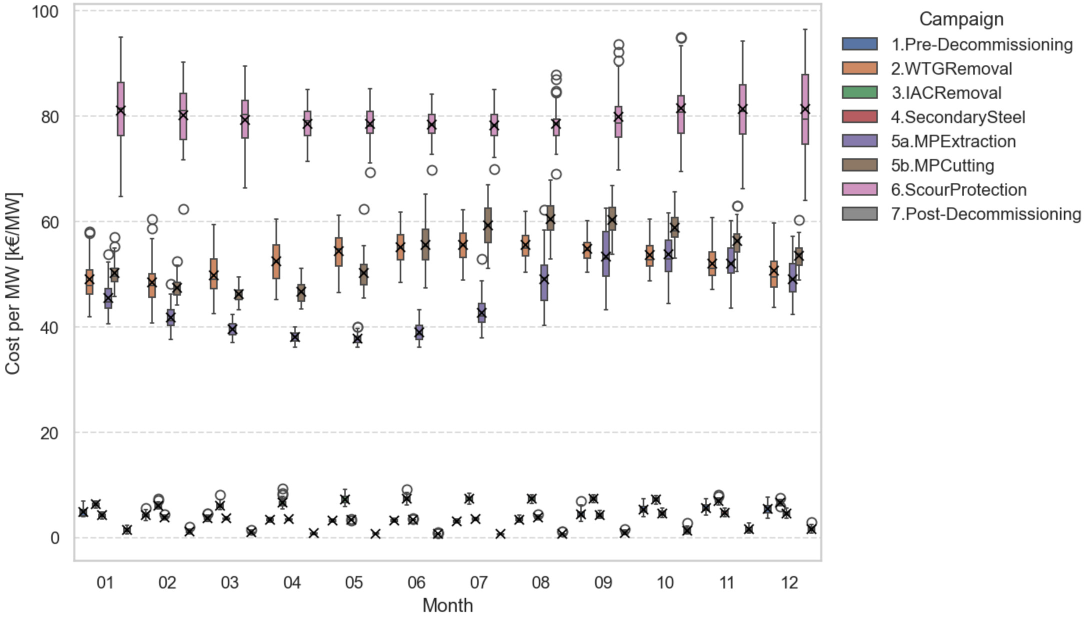

Figure F.5: Distribution of Variation 1 -210km- costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.6 Variation 2 (pessimistic)

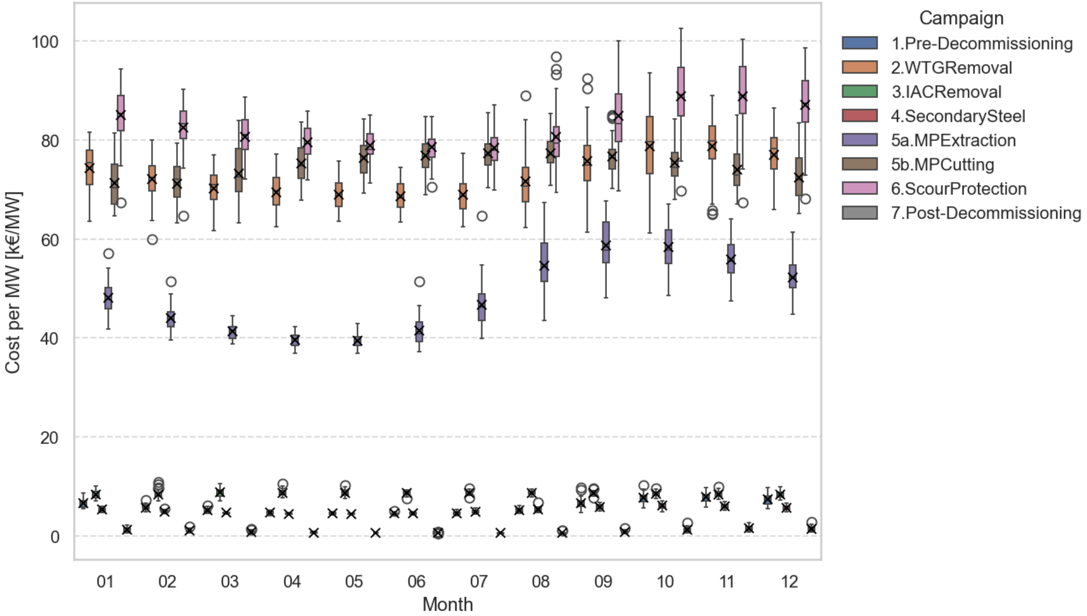

Figure F.6: Distribution of Variation 2 -pessimistic- costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

F.7 Variation 2 (optimistic)

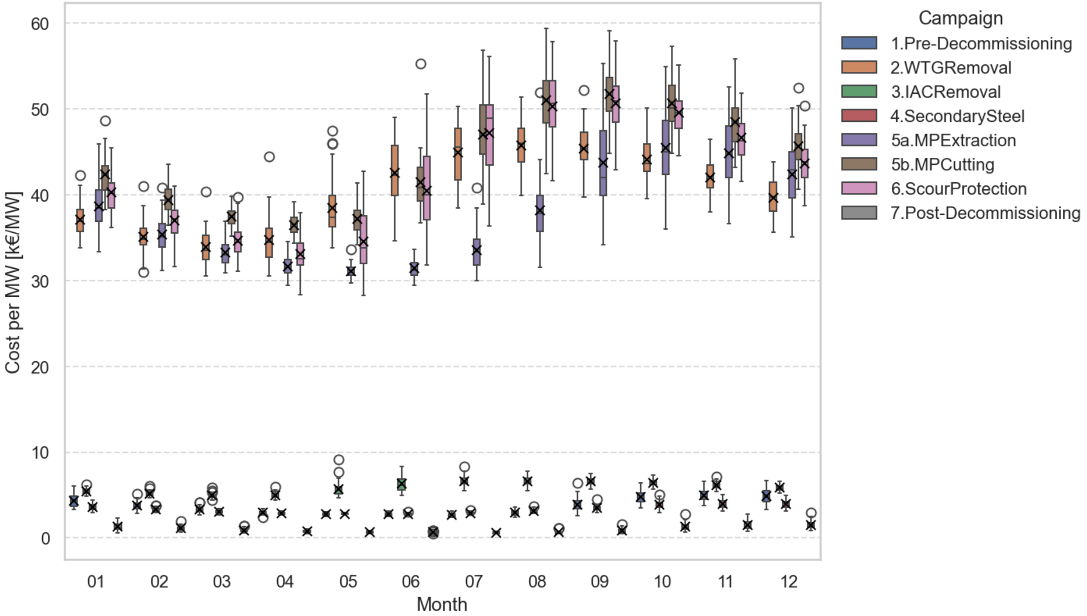

Figure F.7: Distribution of Variation 2 -optimistic- costs for the different campaigns (arranged by color as per the legend on the top right), campaign starting months (x-axis), and 40 weather years (boxplots).

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Kesslerpark 1
2288 GS Rijswijk
www.tno.nl

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