Carbon Footprint of Subsea Leak Detection and Repair

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CARBON LIMITS

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Clients:	Offshore Norge
Project leader:	Maxime Malbranque
QA:	Gaëlle Cauchois
Project members:	Damon Burtt Valentin Gentile Arturo Lopez
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CARBON LIMITS

Stensberggata 27

NO-0170 Oslo

Norge

carbonlimits.no

+47 988 457 930

Carbon Limits works with public authorities, private companies, finance institutions and non-governmental organizations to reduce greenhouse gas emissions from a range of sectors. Our team supports clients in the identification, development, and financing of projects that mitigate climate change and generate economic value, in addition to providing advice on the design and implementation of climate and energy policies and regulations.

Disclaimer

This study aims to inform discussion regarding the implementation of the "Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector"[1] (hereafter EU regulation). Therefore, assumptions were made regarding how subsea practices may be affected by the EU Regulation. Description of practices «as per the EU Regulation» relies on Carbon Limits' interpretation of the regulation text and are only work assumptions intended to set a clear scope and provide informative results. Carbon Limits acknowledges that the EU Regulation contains nuances and provisions and that its implementation may result in situations different from what is described in this study.

The result of this study intends to be representative of current LDAR practices on subsea equipment in the Norwegian continental shelf, but the confidence in the representativeness is limited by data availability. Not all operators of the Norwegian continental shelf have been interviewed, and two service providers communicated information based on their experience. The default, minimum and maximum values collected are the best estimates of service providers and do not result from a statistical analysis of large data records. The default scenario intends to represent an average typical scenario, but the data collection phase highlighted the diversity of cases. The reader is thus invited to consider the ranges of values for each parameter, to assess how the results best apply to a given situation.

The carbon footprint assessment only considers the emissions induced by the fact of conducting LDAR. The emissions due to the leaks themselves are not considered, so the avoidance of emissions in one scenario compared to another is out of scope. Therefore, this study should not be used on its own to quantitatively derive optimum LDAR practices in terms of net emissions.

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- Refine the scope of the study and define current LDAR practices
- Provide some quantitative information
- Facilitate contact with service providers

Carbon Limits also thanks DeepOcean and Sea1Offshore for their valuable inputs. The voluntary participation of service providers has been capital to collect sound estimates for most of the parameters.

[1] "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 Regulation - EU - 2024/1787 - EN - EUR-Lex (europa.eu)

Executive Summary

The Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 (hereafter "the EU Regulation") sets requirements for leak detection and repair (LDAR) practices. The frequencies, quantification requirements and repair limits set by the EU Regulation differ from current practices in Norway. For subsea equipment that are in operation, the EU regulation requires LDAR surveys carried out for all equipment (i.e. components) every 2 years, while there currently is a risk-based approach in Norway. For temporarily plugged wells, the EU regulation requires quantification of methane emissions, while there currently is only requirements for gas leak inspections in Norway.

Conducting offshore, below-sea-level LDAR is energy intensive due to the fuel consumption of transit and operations on site of vessels. Therefore, different requirements of subsea LDAR may lead to significant changes in the emissions of greenhouse gas due to these activities.

While the EU Regulation focuses on LDAR at the component level, this study assesses the carbon footprint of conducting LDAR on subsea equipment following a life-cycle assessment framework. A more detailed approach would complicate data collection without improving the assessment's conclusions, as all components of equipment are typically inspected together (e.g., all valves of a manifold). Therefore, this analysis studies four systems:

1. the inspection of one piece of equipment,
2. the survey with a multi-beam echosounder of one piece of equipment,
3. the quantification of one leak and,
4. the repair of one leak.

The system boundaries include direct emissions due to fuel consumption (travel to site and dynamic positioning), indirect emissions due to the fuel value chain and indirect emissions due to the vessel and remotely operated vehicle life cycles.

Input data to the calculation model were collected from different sources:

- 7 oil and gas operators having operations on the Norwegian continental shelf were interviewed.
- 2 providers of survey, inspection and maintenance services operating on the Norwegian continental shelf completed a data collection template.
- Geographical parameters such as the distances between inspection sites, distance to shore, number of equipment pieces per site and depth were derived from datasets published by the Norwegian Offshore Directorate (Sodir).
- Additional information on vessels and ROV was extracted from service provider websites.

To reflect the diversity of real-life conditions, a range of values was collected for each parameter. Results are calculated for a default scenario which intends to represent a typical average case (see table below), but results may vary significantly with varying parameters. Therefore, a sensitivity analysis was carried out to explain how the changes in parameters affect the carbon footprint.

Table 1 – Summary of average results: carbon footprint of equipment inspection, equipment survey, leak quantification and leak repair.

	Active wells – shallow water	Active wells – deep water	Temporarily abandoned wells – shallow water	Temporarily abandoned wells – deep water	Manifolds	Risers and riser bases
Equipment inspection (tCO_2e / equipment)	10.9	15.8	6.0	7.2	17.0	14.5
Equipment survey (tCO_2e / equipment)	4.4	5.8	2.9	3.2	6.2	5.4
Leak quantification (tCO_2e / leak)	9.9					
Leak repair (tCO_2e / leak)	217					

Source: Carbon Limits analysis, 2024

The parameters impacting the results the most are:

- The time needed on site to carry out the inspections, leak quantification and repair. Repair time varies greatly as there is no typical repair for subsea equipment.
- The number of sites inspected during the same vessel mobilization.
- The type of vessel used.
- The distance from vessel supplier's base to quayside in the case of remote locations.

Results are put in perspective with possible emission rates. For instance, inspecting one active well in shallow water every 2 years leads to the same emissions as a subsea leak continuously emitting at a rate of 21 gCH_4 / h, assuming a 100% transport of methane from the seafloor to the surface. Inspecting manifolds every 2 years instead of 3 causes a surplus in carbon footprint equivalent to a subsea leak continuously emitting at a rate of 11 gCH_4 / h, assuming a 100% transport of methane to the surface. Previous studies showed that the share of methane reaching the surface varies with the depth of release. In practice, subsea leak rates must therefore be larger than the ones calculated in this study to lead to the same greenhouse gas emissions to air.

When it comes to leak repair, for leak rates around the repair limit of 17 gCH_4 / h set in the EU Regulation, the emissions of travel to site may in some situations exceed the emissions caused over several years by the leak, resulting in a higher climate impact than the leaks themselves. The average carbon footprint of performing a leak repair is determined to be 217 tCO_2e which is equivalent to a subsea leak of 17g/h continuing for 49 years. The sensitivity analysis demonstrates the high dependency results to in-field conditions. Therefore, the results of the analysis may not be representative of all scenarios, and the conclusions must be carefully considered on a case-by-case basis.

This study is limited to the carbon footprint of conducting the LDAR. It could be complemented by an analysis of the magnitude and occurrence of observed leaks to compare the results obtained to potential avoided emissions. Several assumptions could also be refined to consolidate the results, especially for equipment survey.

Table of Contents

Acknowledgements ii
Executive Summary iii
Abbreviations 1
1 Introduction 2
1.1 Context for the study 2
1.2 Definitions 3
1.3 Equipment and practices studied 4
2 Goal and scope definition 8
2.1 Goal of the assessment 8
2.2 Scope of the assessment 8
2.3 System boundaries 9
2.4 Data sources and quality characterization 12
2.5 Geography and time coverage 17
3 Life cycle inventory 18
4 Impact assessment and results interpretation 20
4.1 Equipment inspection 20
4.2 Equipment Survey 21
4.3 Leak quantification and repair 22
4.4 Emission Factors 23
4.5 Sensitivity Analysis 24
4.6 Carbon Footprint of LDAR practices in scenarios as per the EU Methane Regulation 29
5 Conclusion 34
Annex A. Pipelines: parameters and preliminary results 36
Annex B. Calculation model 38
B.1 Equipment inspection 38
B.2 Equipment survey 38
B.3 Leak quantification 39
B.4 Leak repair 40
Annex C. Sensitivity analysis 41
C.1 Equipment inspection 41
C.2 Equipment survey 44
C.3 Leak quantification 46
C.4 Leak repair 47

Abbreviations

EU	European Union
IMR	Inspection, maintenance and repair
LDAR	Leak detection and repair
LNG	Liquefied natural gas
MBES	Multi-beam echosounder
MDO	Marine diesel oil
MGO	Marine gas oil
PSV	Platform supply vessel
ROV	Remotely operated vehicle
tCO_2e	Ton carbon dioxide equivalent

1 Introduction

1.1 Context for the study

Leak detection and repair (LDAR) at oil and gas production facilities is a way to mitigate methane emissions by reducing the frequency and severity of fugitive emissions[2], i.e. leaks. Generally, technologies such as soap spraying, optical gas imaging, laser absorption spectroscopy, or metal oxide semiconductors can be used to detect natural gas leaks. The leak rate can subsequently be measured at or in proximity to the emission source using technologies such as a high flow sampler or a calibrated bag[3]. According to the best industry practices, the detected leaks are tagged, repaired and finally inspected again to verify the effectiveness of the repair[4]. However, in the case of production equipment under the sea level, LDAR causes additional challenges:

- Traditional detection and quantification technologies used for ambient measurement of methane do not function underwater,
- The number of technologies currently applicable for subsea natural gas detection and flow rate quantification is limited,[5]
- Natural seepage may occur in the vicinity of the equipment, requiring additional steps to distinguish biogenic or geological methane from fossil gas leaks,[6]
- The propagation of methane through the water column from the emission point to the surface involves several mechanisms very dependent on ambient conditions: direct bubble transport, dissolution, turbulent mixing and biodegradation. These mechanisms play different role depending on the water depth,[7]
- It is necessary to deploy a vessel to the offshore site where the equipment is and then to stabilize the vessel for a long enough duration to carry out the detection and quantification or repair.

The latter point implies that subsea LDAR leads to significant fuel consumption which ultimately leads to emissions of greenhouse gas. To understand the scale of these emissions, Offshore Norge commissioned Carbon Limits AS to perform an assessment of the carbon footprint of subsea LDAR. This study was conducted in the context of the new Regulation of the European Parliament and of the Council on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 (hereafter "the EU Regulation") adopted in July 2024.[8] The EU Regulation prescribes requirements for subsea LDAR and the inventory of emissions of subsea wells, which may differ from practices currently implemented in Norway. Therefore, this study investigates how the EU Regulation may influence different LDAR operating parameters, and how these may impact the carbon footprint of these altering practices.

The present report explains the methodology followed and the results of the carbon footprint study. The assessment was performed following the ISO standards 14040, «Life Cycle Analysis – principles and framework», and 14044, «Life Cycle Analysis – requirements and guidelines». The report is structured according to the standards with the following parts:

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[2] A. P Ravikumar et al. "Repeated leak detection and repair surveys reduce methane emissions over scale of years". *Environ. Res. Lett.* Vol 15 no 3. 2020. DOI 10.1088/1748-9326/ab6ae1

[3] *Approved baseline and monitoring methodology AM0023*. UNFCCC. https://cdm.unfccc.int/UserManagement/FileStorage/LV8NU1GYWTK06COJPDIXQ35FR2MA47

[4] "Best Practice Guides: Equipment Leaks". Methane Guiding Principles. 2024. [Online]. https://methaneguidingprinciples.org/wp-content/uploads/2024/05/MGP2024_Best-Practice_Leaks_FINAL.pdf

[5] "Overview of Subsea methane Emissions Detection and Quantification Technologies". Carbon Limits AS [Online]. https://www.carbonlimits.no/projects/overview-of-subsea-methane-emissions-detection-and-quantification-technologies-6xw7y

[6] "DNV-RP-F302 Offshore leak detection Recommended Practice". DNV. [Online] https://www.dnv.com/oilgas/download/dnv-rp-f302-offshore-leak-detection/

[7] T. Nordham, A.L. Dissanatake, O. G. Brakstad. "Methane seeps – A desktop study". SINTEF. [Online]https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2730544

[8] "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942 Regulation - EU - 2024/1787 - EN - EUR-Lex (europa.eu)

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Results interpretation

1.2 Definitions

This study uses several technical terms related to oil and gas operations and methane emissions mitigation that may have different meanings for different stakeholders. Therefore, for the sake of this study, the following terms should be understood as follows:

Active well: oil or gas production well in operation.

Deep water: water depth greater than 200 meters.[9]

Demobilization site: vessel provider's site where the vessel is kept when not in operation.

Inspection: close-distance observation of a piece of equipment to verify its integrity and detect leaks. In this study, it is assumed that inspections are systematically performed using remotely operated vehicles, typically equipped with an optic or acoustic sensor.

Inspection site: above-sea location under which one or several pieces of equipment are located. The vessel stays static at this location while all equipment pieces under are inspected (see Figure 1).

Leak: An unintentional emission of fossil gas released by subsea equipment into water. Methane emissions in water can come from leaks or from other sources such as seepage of natural geological fossil methane.[10] Leaks are generally coming from abnormally functioning equipment that have the potential to be fixed.

Leak detection: observation of a leak from equipment, as a conclusion of either an inspection or a survey.

Leak detection and repair (LDAR): practices in place to identify and detect sources of methane leaks and other unintentional methane emissions, and to repair or replace the relevant components.[11]

Leak quantification: quantification of the amount of methane released to water by a leak.

Multi-beam echosounder (MBES): sonar installed on vessels that sends sound waves and measures the elapsed time between the emission of the signal and the reception after reflection on a reflective object. Gas bubble in water can be detected from afar[12] with that method.[13]

Permanently abandoned well: a well that is plugged and abandoned (secured) with a dual barrier, where the intention is not to re-enter the well again, *e.g.,* all equipment is cut below seabed and removed.

Quayside: port onshore from which the vessel travels to the inspection site.

Remotely operated vehicle (ROV): submersible robot remotely piloted used for various underwater tasks.

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[9] Adapted from International Hydrographic Organization Standards for Hydrographic Surveys. (https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf) based on surveying depths, as well as EU Methane Regulations where 200 m refers to the possible exemption of inspection of inactive or plugged wells below this depth.

[10] P. Serov et al. "Widespread natural methane and oil leakage from sub-marine Arctic reservoirs" *Nat. Commun.* Vol 14 2023. DOI 10.1038/s41467-023-37514-9

[11] Adapted from article 2, "Definitions" of the EU Regulation

[12] Distance of detection depends on leak size and visibility. Small gas leaks (bubble diameter = 0.35 mm) can be seen up to 125 m range, but the range can be longer for larger leaks. Source : https://www.dnv.com/oilgas/download/dnv-rp-f302-offshore-leak-detection/

[13] P. Serov et al. "Widespread natural methane and oil leakage from sub-marine Arctic reservoirs" *Nat. Commun.* Vol 14 2023. DOI 10.1038/s41467-023-37514-9

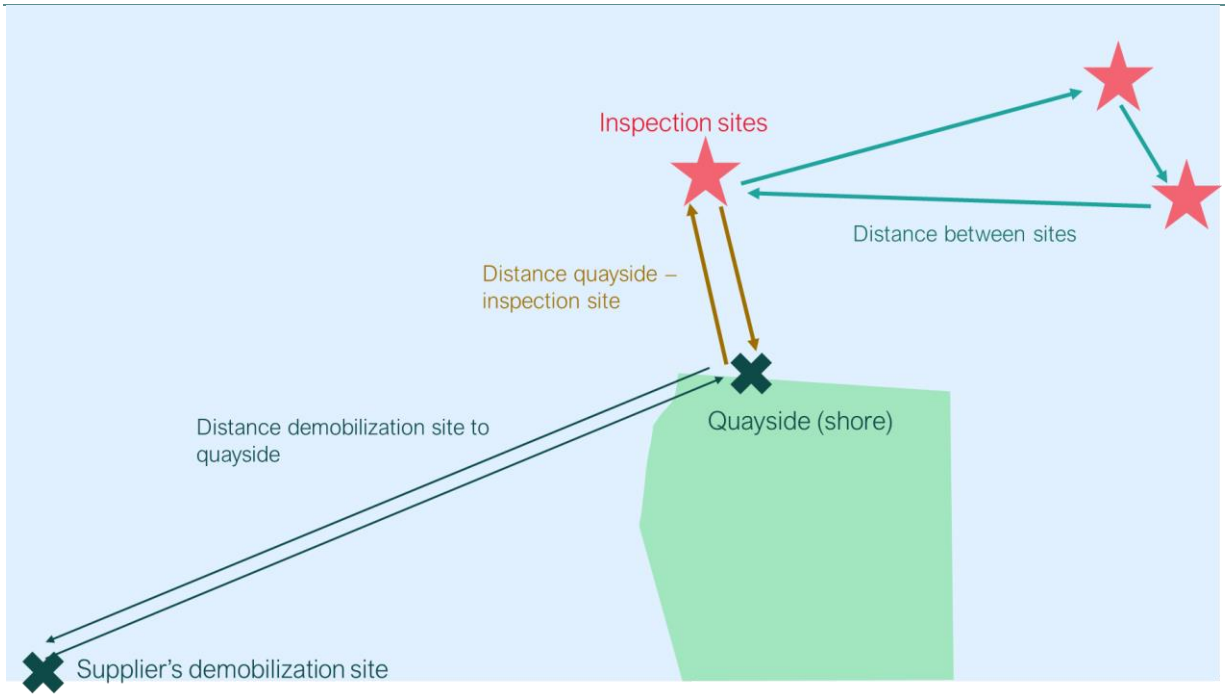
Shallow water: water depth shallower than 200 meters.[14]

(MBES) Survey: Long distance observation of equipment (and surroundings) with a multi-beam echosounder mounted on a vessel. In this study, the word survey is exclusively used for MBES survey, while in the EU Regulation the word "survey" is generic and used for all kinds of LDAR practices.

Subsea: offshore under the sea level. The scope of the study is exclusively about subsea equipment and leaks. Subsequently, all equipment and leaks mentioned in this report are to be considered subsea.

Temporarily abandoned well: a well that is plugged and abandoned (secured) with a dual barrier, with the intention to re-enter the well again to either start production or permanently plug it.

Figure 1 – Illustration of the different distances considered in the model



Source: Carbon Limits, 2024

1.3 Equipment and practices studied

The choice of equipment and practices to include in the study was guided by the current practices described by 7 operators interviewed during the project and by the requirements set in the EU Regulation, in articles 14 ("Leak detection and repair") and 18 ("Inactive wells, temporarily plugged wells and permanently plugged and abandoned wells").

The statements in this section rely on Carbon Limits' understanding of how the EU Regulation may apply to subsea equipment. They are work assumptions intended to set a clear scope and provide informative results. Carbon Limits acknowledges that the EU Regulation contains nuances and provisions and that its implementation may result in situations different from what is described in this study.

[14] Adapted from International Hydrographic Organization Standards for Hydrographic Surveys. (https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf) based on surveying depths, as well as EU Methane Regulations where 200 m refers to the possible exemption of inspection of inactive or plugged wells below this depth.

Detection method

Article 14 of the EU regulation states that LDAR of subsea equipment shall be carried out "applying the best detection techniques that are commercially available". Therefore, the impact of equipment inspection with ROV is assessed, as it is the main detection technique used by operators. The ROV is equipped with an optical or acoustic sensor to detect gas bubbles in water near the equipment. In this study, no distinction is made between the types of sensors that may be used.

In the study, multi-beam echosounder (MBES) survey is included as an alternative technique for leak detection. Even though it is not a widespread leak detection method, some information is available based on operators and service providers' experience.

The systems at scope correspond to best available technologies in Norway as per 2024. New technologies or techniques may develop in the future and may result in different carbon footprint for subsea LDAR.

LDAR frequencies

Article 14 of the EU regulation defines two types of LDAR with different repair thresholds and frequencies.[15] However, in the case of subsea equipment, there is no distinction: for all equipment below the sea level and above the seabed LDAR shall be carried out at least every 24 months, and the repair limit is 7000 ppm or 17 gCH_4/h. A reduction in the frequencies is possible if emissions below a given threshold[16] are recorded five years in a row, bringing the minimum frequency of LDAR to 36 months for production locations (Type 1 LDAR). Subsea equipment located at a water depth greater than 700 meters may be exempted by competent authorities.

As part of the requirements set in article 18, emissions from temporarily abandoned wells must be quantified each year. Therefore, even if they are not covered by LDAR requirements (article 14), temporarily abandoned wells may also be subject to leak detection. The reporting obligations may be lifted for offshore wells that have demonstrated no methane emissions within the last three years. Wells located at a water depth greater 200 meters may also be exempted by competent authorities.

The Norwegian regulation imposes maintenance programs for active wells and temporarily abandoned wells. Maintenance programs are complemented by a risk-based assurance. Consequently, operators report that, as a baseline, wells are inspected yearly. Some are inspected more often, some less. Once secured with two barriers, the equipment removed and well controlled, permanently abandoned wells are not subject to further inspection programs.[17]

Similarly to active and temporarily abandoned wells, the baseline frequency for riser inspection is one year.[18] The effective frequency may be more or less depending on a risk assessment. For all other equipment, the decision to inspect equipment is based on a risk assessment conducted by the operator. Parameters such as the equipment age, the location, results from earlier inspections and history of incidents are evaluated for each piece of equipment. As a result, there is no pre-defined frequency for inspection.

[15] Type 1 and Type 2 LDAR for which the requirements are described in Article 14(2), (7) and (8) and Part 1 of Annex I in the EU Regulation. Generally, Type 2 LDAR is stricter than Type 1 (*e.g.*, lower repair limit) but can be done less frequently.
[16] Meaning that annual monitoring reports during five preceding years show that less than 1 % of all components and subcomponents in each site are leaking and methane emissions associated with these leaks aggregated represent less than: 0.08% of the total volume of gas or 0.015% of the total mass of oil processed or extracted.
[17] Temporarily plugged and abandoned wells, Havtil (Norwegian Ocean Industry Authority). Accessed July 2024. Tema: Midlertidig pluggede og forlatte brønner (havtil.no)
[18] § 47 Maintenance programme, The activities regulations, Havtil (Norwegian Ocean Industry Authority). Accessed July 2024. All regulations (havtil.no)

Leak quantification

In the EU Regulation, quantification is defined as "activities to determine the quantity of methane emissions by means of direct measurements or, where direct measurements are not feasible, based on other methods such as simulation tools, and other detailed engineering calculations or a combination of such methods".

A previous report showed that currently available technologies for subsea leak detection can quantify emissions of gas to water but not of methane specifically.[19] Therefore, in this study, it is assumed that leak quantification relies on a combination of gas rate estimation and gas analysis to determine the methane content. This is a modelling assumption, and other quantification methods may be valid either relying on calculations or on new technologies becoming available in the future. In this study, leak quantification is also limited to emissions to water. It is assumed that emissions to air would be derived from emissions to water through additional processing such as simulation.

In Norway, leak quantification is not systematically performed when a leak is detected. When it is performed, the quantification method is not standardized. Operators report that gas sampling may typically be done to determine the origin of detected gas: to differentiate between biogenic and fossil gas or to identify the field the gas comes from. Operators also report that gas rate is sometimes measured, but not performed simultaneously with gas sampling.

According to article 18 of the EU regulation, the inventory of all inactive and temporarily abandoned wells shall include information on "results of quantification of methane emissions to air and to water carried out", including quantification of methane emissions to air and to water[20], and information on pressure monitoring - where such equipment exists. This may include a requirement for quantification of emissions of all permanently plugged and abandoned wells. The inventory shall be established within one year after the entry into force of the regulation and the Member State must ensure it is maintained and kept up to date, but there is no explicit requirement for the frequency of the update.

Leak repair

Article 14 of the EU Regulation sets a repair limit, where all subsea components found to be emitting more than 17 g/h or 7000 ppm shall be repaired or replaced. The repair shall take place immediately after detection, or as soon as possible for a first attempt within 5 days of detection and 30 days for a complete repair. An extended repair and monitoring schedule may be accepted according to strict conditions by the authorities.

When emissions are released from inactive and temporarily abandoned wells, there is also an obligation to mitigate the leak by taking "all the necessary measures available […] for remediating, reclaiming and permanently plugging" the well, "as applicable, where technically feasible and taking into account the environmental impact of the necessary works in view of the associated reduction of the methane emissions" (article 18).

In the Norwegian regulation, the acceptable leak rate for subsea equipment is "zero" meaning that all detected leaks must be fixed. However, the repair schedule is based on a risk analysis: depending on the magnitude of the emissions and the risk of escalation, the timeline for repair varies.

Equipment types

This study assesses the carbon footprint of leak detection and repair on subsea wells. Based on the distinctions made in the EU regulation, wells are divided into categories based on their activity (active *vs.* temporarily abandoned) and their water depth (shallower or deeper than 200 meters). Based on interviews

[19] "Overview of Subsea methane Emissions Detection and Quantification Technologies". Carbon Limits AS [Online]. https://www.carbonlimits.no/projects/overview-of-subsea-methane-emissions-detection-and-quantification-technologies-6xw7y

[20] In this study, this sentence is understood as meaning quantification of methane emissions to air from onshore wells and to water from offshore wells.

with operators, two other types of equipment are included in the assessment: risers (and riser bases) and manifolds. Since the approach to inspection in Norway is risk-based, the operators provided a range of current inspection frequencies for these equipment types, that correspond to observed frequencies.

A summary of the equipment at scope and how the LDAR practices are applied to them following current practices and requirements set by the EU Regulation is available in Table 2. It should be noted that the EU Regulation addresses LDAR in terms of component, while this study quantifies the carbon footprint of leak detection at equipment level. Using a more granular approach would be challenging in terms of data collection and would not refine the conclusions of the assessment. Indeed, all components of a piece of equipment are generally inspected or surveyed during the same deployment (*e.g.*, all valves of a manifold).

Table 2 – Comparison of current LDAR practices in Norway and requirements set by the EU Regulation for the subsea equipment considered in the study

Equipment	Inspection frequency – Currently in Norway	Inspection frequency – EU regulation	Leak quantification – Currently in Norway	Leak quantification – EU Regulation	Leak repair – Currently in Norway	Leak repair – EU Regulation
Active wells – shallow water	Risk-based (otherwise every year). Observed: every 0.5 to 1.5 years on average.	Every 2 years.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required within 30 days max for leaks > 17 g/h.
Active wells – deep water[21]	Risk-based (otherwise every year). Observed: every 0.5 to 1.5 years on average.	Every 2 years.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required within 30 days max for leaks > 17 g/h.
Temporarily abandoned wells – shallow water	Risk-based (otherwise every year). Observed: every 0.5 to 1.5 years on average.	Every year. Relief after 3 years if no emissions.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required.
Temporarily abandoned wells – deep water	Risk-based (otherwise every year). Observed: every 0.5 to 1.5 years on average.	Every year. Relief after 3 years if no. May be exempted.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required.

[21] As a reminder, the separation between shallow and deep water is set at 200 meters water depth.

Equipment	Inspection frequency – Currently in Norway	Inspection frequency – EU regulation	Leak quantification – Currently in Norway	Leak quantification – EU Regulation	Leak repair – Currently in Norway	Leak repair – EU Regulation
Manifolds	Risk-based. Observed: every 4 to 5 years in average.	Every 2 years. Every 3 years if emissions below threshold for 5 preceding years.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required within 30 days max for leaks > 17 g/h.
Risers and riser bases	Risk-based (otherwise every year). Observed: every 1 to 3 years on average.	Every 2 years. Every 3 years if emissions below threshold for 5 preceding years.	Not systematic.	Required.	All leaks to be repaired. Risk based schedule applies	Required within 30 days max for leaks > 17 g/h.

Pipelines have been considered as an additional type of equipment but have been excluded from the scope of the study. The calculation model is not fitted for this type of equipment: as the length of pipeline may vary significantly, the time needed for inspection, survey or repair may also vary greatly. With reference to the definition of components, pipeline inspection may refer to inspection of components along the pipeline. Therefore, calculating the carbon footprint of LDAR per pipeline may lead to results that are not representative of actual practices. Operators and service providers have supplied some data on the inspection and surveying of entire pipelines, but the data is varied and may not cover all scenarios. They are presented alongside preliminary results in Appendix Annex A for information purposes. This may serve as a basis for a more extensive data collection in the context of a study with a model refined for pipelines. More appropriate functional units could involve calculation of emissions per unit-length of pipeline or per equipment along the pipeline.

2 Goal and scope definition

2.1 Goal of the assessment

The goal of the assessment is to quantify the greenhouse gas emissions due to conducting LDAR on subsea equipment in Norway. Among other applications, this report is intended to be used by Offshore Norge in its discussion with regulators regarding the design and implementation of the EU regulation.

2.2 Scope of the assessment

Leak detection and repair encompasses several activities that may be conducted separately and differently depending on the regulatory requirements. Therefore, four independent systems are studied and described in Table 3. Equipment inspection and equipment survey are considered two different systems fulfilling the same goal: to detect leak on subsea equipment.

Table 3 – Systems and functional units at scope for the carbon footprint assessment

Product system	Function of the product system	Functional unit
Equipment inspection	Go to the location of subsea equipment and inspect the equipment to verify integrity and detect gas leaks.[22]	To inspect once 1 piece of equipment, under the sea level, on the Norwegian continental shelf.
Equipment survey	Go to the location of subsea equipment and screen for leaks using a multi-beam echosounder. In case of emission detection, carry out an inspection to confirm the presence of leak.	To survey once 1 piece of equipment, under the sea level, on the Norwegian continental shelf, and inspect the equipment in case of emission detection.
Leak quantification	When positioned above the location of 1 piece of equipment with detected leak, sample the leak and quantify the emission rate.	To sample and quantify once the rate of 1 detected leak on 1 piece of equipment, under the sea level, on the Norwegian continental shelf.
Leak repair	Go to the location of subsea equipment with detected leak and repair the leak.	To repair 1 leak once on 1 piece of equipment, under the sea level, on the Norwegian continental shelf.

For all four systems, the assessment is performed for practices currently in place in Norway in 2024. The scope of the study is restricted to the greenhouse gas (GHG) emissions caused by LDAR activities. The study **does not account for the emissions due to the leaks themselves**, and therefore does not evaluate emissions that are avoided in one scenario compared to another.

The environmental impact indicator assessed in the study is the Global Warming Potential at 100 years (GWP100), which provides a common measurement unit for all GHG in ton of carbon dioxide equivalent (tCO_2e). Quantities of gas emitted are converted to tCO_2e using the GWP100 values indicated by the 6th Assessment Report of the International Panel on Climate Change.[23]

2.3 System boundaries

The systems studied are described in Figure 2 to Figure 5. For each system, the chosen scope includes:

- The emissions to air due to fuel combustion during travel to sites and operations
- The upstream emissions due to the value chain of the fuel
- The emissions due to production and end-of-life of the vessel
- The emissions due to production and end-of-life of the ROV

Due to low environmental significance in terms of global warming potential, the following items are excluded from the scope:

- Emissions due to the manufacturing, transport, operation and end-of-life of detection, quantification and repair tools such as cameras and sampling bottles.
- Emissions due to data management and remote operation of the ROV.

[22] In practice, the goal of equipment inspection is not to only detect existing leaks but to also anticipate future malfunctions or leak by checking the equipment status.
[23] C. Smith et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material". In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* 2021. Available from https://www.ipcc.ch/.

- Emissions occurring at the laboratory during analysis of the sampled gas (leak quantification).
- Emissions due to the subsistence of the workforce onboard the vessel: food production and transport, waste and wastewater generation.

Additionally, the following item is excluded due to lack of data:

- Emissions due to manufacture and transport of repair material for leak repair: as there is no typical repair, there is a large range in terms of mass, nature, origin and complexity of the material.

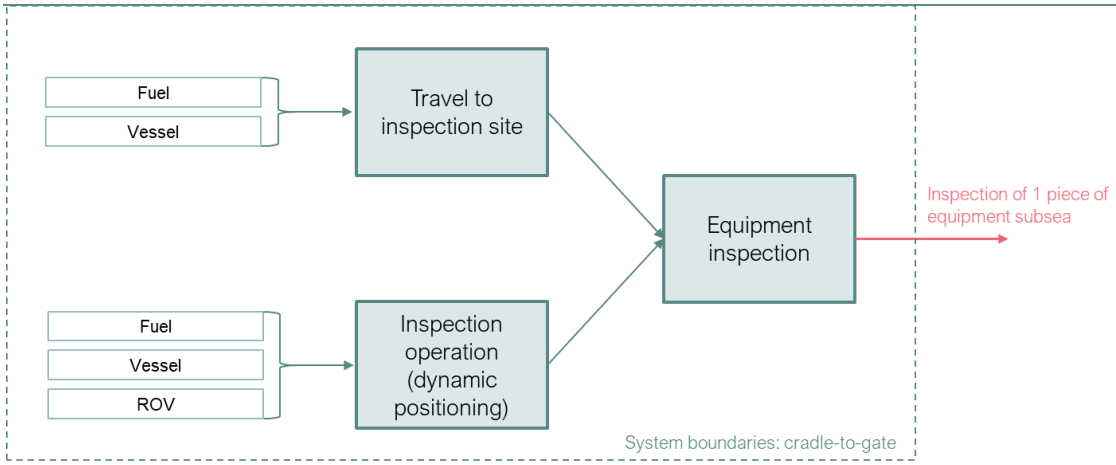
The impacts linked to repair material might not be negligible compared to impacts linked to ROV. There are however expected to be negligible compared to fuel consumption. The analysis of results in section 4 shows that 99% of the emissions are due to fuel (combustion and value chain). Therefore, including other equipment than vessel and ROV in the scope would add complexity and uncertainty in the data collection and would bring marginal changes in the results.

Equipment inspection

Equipment inspection includes the travel time and distance from the quayside to an inspection site, and the distances between subsequent inspection sites. The distance from demobilization site to quayside is not included in the default scenario because of the high variability of situations: the vessel can come from the mobilization site, while it can also already be at the quayside (if for example it was already in use for other activities), or can come from another port, or from a field directly. A sensitivity analysis is performed on the impact of including or not the distance between demobilization site and quayside (see Section 4.5).

The equipment inspection also considers the carbon footprint of dynamic positioning, in which the vessel is held stationary during the time that the ROV is performing the inspection on site, thus consuming additional fuel and operating time. Inputs for dynamic positioning were provided by operators and service providers on a per equipment basis.

Figure 2 - System boundaries of equipment inspection



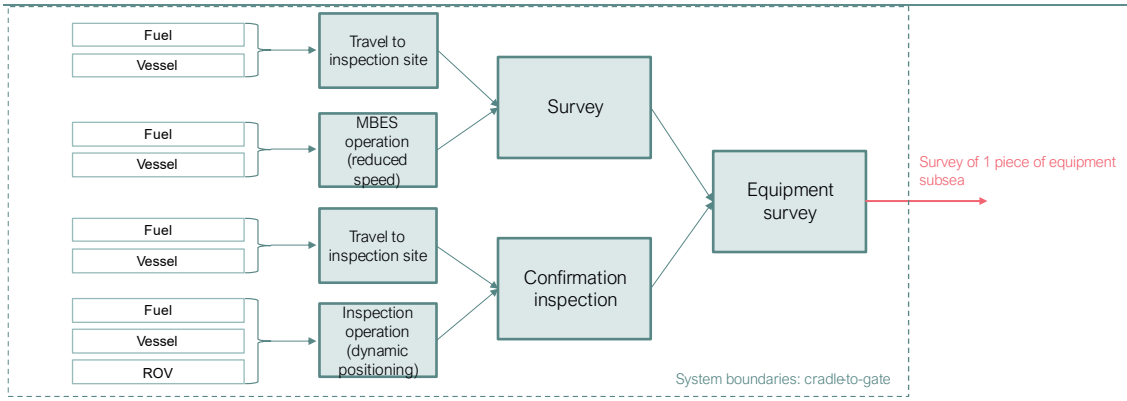
Equipment survey

An equipment survey includes two activities. First, it includes a survey with a multi-beam echosounder which consists of two steps: the travel to site (following the same ways and means as equipment inspection) and then the use of the multi-beam echosounder “on the spot” (the vessel is not completely static but travels at reduced speed). The system model for the survey is the same as the one for equipment inspection but with less time spent per equipment piece, more equipment pieces surveyed per site (all equipment in the area is surveyed simultaneously) and more sites covered by mobilization.

The second activity in the system is a confirmation inspection. If emissions are detected during the survey, then a second vessel mobilization is carried out to inspect the equipment nearby which emissions have been

detected to confirm if there is an actual leak. In the model, the confirmation inspection is the same as the one described above in Figure 2. An assumption is made regarding the share of equipment for which a confirmation inspection is necessary. In practice, the vessel equipped with the MBES may in some cases have a ROV onboard and the inspection may therefore be carried out during the same vessel mobilization as the survey. This may lead to a lower carbon footprint of the "survey and confirmation" operation. However, the scenario of an independent confirmation inspection was preferred for this assessment as it is more conservative.

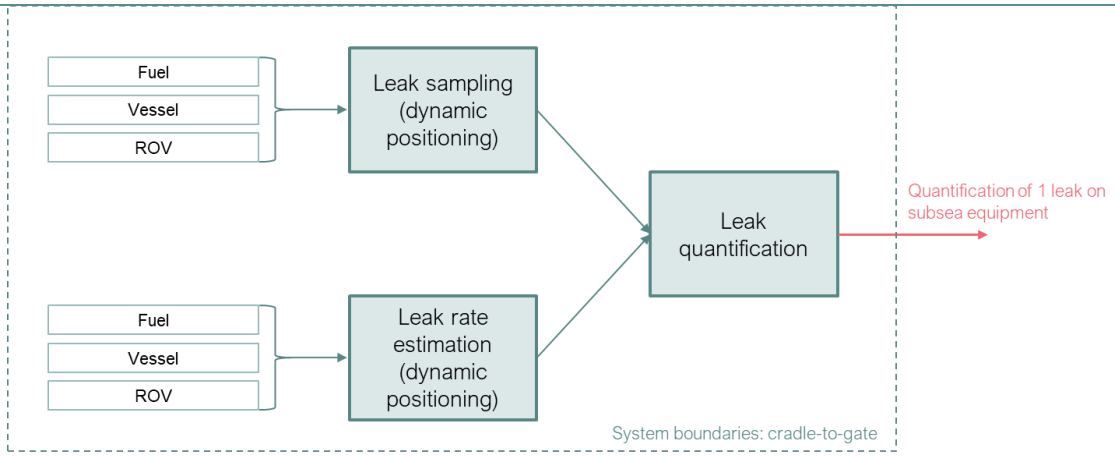
Figure 3 - System boundaries of equipment survey



Leak quantification

The system boundaries of equipment inspections include the leak sampling, and leak rate estimation. The leak sampling is the time that it takes to collect gas from the emission source, typically with a sampling bottle. The leak rate estimation is the time that it takes to determine the flow rate of leaking equipment. To perform these activities, dynamic positioning is also required to hold the vessel stationary while the ROV performs activities, consuming additional fuel and operating time. Inputs to these variables were provided by operators and service providers on a per equipment basis. Since quantification is assumed to be performed immediately after inspection (assuming equipment and tools for quantification are already onboard the vessel at the time of inspection), no traveling is associated with leak quantification activities. It is however assumed that leak quantification requires some set-up after leak detection: to retrieve the tools from the vessel and to wait for stabilization of the environment.

Figure 4 - System boundaries of leak quantification

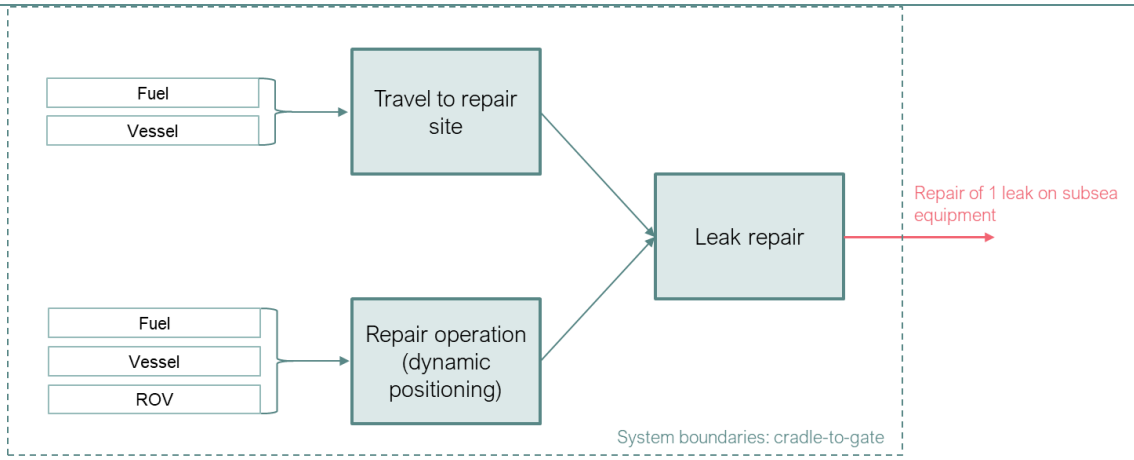


Leak repair

The system boundary of a leak repair assumes travel to site and the dynamic positioning during repair operations. It is assumed that repairs are performed in a subsequent deployment, because the vessels used

to carry out inspection seldom have the required tools and material onboard for a repair. Like an equipment inspection, the distance from the mobilization site to the quayside is not included in the default scenario. It is assumed that only one site is visited during a leak repair. The system also includes dynamic positioning during repair operations. The repair times were provided directly per piece of equipment by the operators and service providers.

Figure 5 - System boundaries of a leak repair



2.4 Data sources and quality characterization

The carbon footprint of the different activities at scope is calculated by multiplying activity data by emission factors. The activity data is the consumption of fuel during traveling and during dynamic positioning (DP), and the number of vessels and ROV needed to fulfil the functional unit. The calculations are summarized as follows:

$$Carbon\ footprint =$$

$$\left(Time_{Traveling} \times Fuel\ consumption_{Traveling} + Time_{DP} \times Fuel\ consumption_{DP}\right) \times Emission\ factor_{fuel}$$
$$+ \left(Time_{Traveling} + Time_{DP}\right) \times \left(\frac{Emission\ factor_{Vessel}}{Lifetime_{Vessel}} + \frac{Emission\ factor_{ROV}}{Lifetime_{ROV}}\right)$$

Travel time and time on site

For each system, the travel time ($Time_{Traveling}$) and the time spent on site using dynamic positioning ($Time_{DP}$) are calculated per functional unit with a combination of parameters. The calculations used to model the different systems are detailed in Appendix Annex B.

The parameters were collected from different sources:

- 7 oil and gas operators having operations on the Norwegian continental shelf have been interviewed. They provided information about the programming of subsea LDAR activities in their company, about the type and location of their equipment and gave estimates for the time required for different activities.
- 2 providers of survey, inspection and maintenance services operating on the Norwegian continental shelf completed a data collection template. They provided information about the time required for different activities, about the characteristics of vessels and ROV used and about the organization of inspection and survey campaigns.

- Geographical parameters such as the distances between inspection sites, distance to shore, number of equipment pieces per site and depth were derived from datasets published by the Norwegian Offshore Directorate (Sodir). The dataset of fixed facilities[24] and of wellbores[25] was used.
- Additional information on vessels and ROV was extracted from service provider websites.

Table 4 displays the complete list of parameters used for the calculations of the carbon footprint. Each parameter is explained and the source for the data is given. A characterization of the level of confidence is also displayed.

Table 4 - Description of the input parameters and source for the data

Systems	Parameter	Description	Source	Confidence
Equipment inspection, Equipment survey, Leak repair	Distance between sites	Distance between two consecutive sites inspected during a same mobilization.	Sodir's datasets of fixed facilities[26]. Default value calculated as average distance assuming 1 facility = 1 site. Minimum and maximum given by service providers.	Medium
	Distance quayside - site	Distance between the onshore port and the closest site to inspect / survey	Sodir's datasets of fixed facilities. Closest distance to the Norwegian continental shore.	High
	Distance demobilization site - quayside	Distance between the service provider's base and the onshore port.	Assumed 0 in default. Only accounted to discuss assumption regarding scope. Sodir's datasets of fixed facilities. Closest distances between facilities and ports in Stavanger, Bergen and Trondheim.	High
Equipment inspection, Equipment survey	Number of sites inspected	Number of sites inspected during a same mobilization.	Service providers	High
	Number of equipment pieces inspected by site	Number of elements inspected on a same site.	Interviews with operators and Sodir's datasets. Default value for wells: average by corresponding the number of wells to the number of fixed facilities by field.	High

[24] Fact pages, Table – Fixed, Norwegian Offshore Directorate. Accessed in February 2024. Facility: Fixed - Factpages - Norwegian Offshore Directorate (sodir.no)
[25] Open data, dataset "Wellbore", Norwegian Offshore Directorate. Accessed in April 2024. Open data - The Norwegian Offshore Directorate (sodir.no)
[26] Facilities filtered to only retain "single well template" and "multi well template", excluding water injection, CO_2 production and CO_2 injection

Systems	Parameter	Description	Source	Confidence
	Inspection time per equipment	Time required for the inspection of 1 equipment piece.	Service providers	High
	Allocation of mobilization to inspection	Share of the vessel mobilization dedicated to inspection. If other activities are performed, the share is less than 100%.	Interviews with operators. Difficult to assess due to high variability in planning.	Medium
Equipment survey	Number of sites surveyed	Number of sites surveyed during the same mobilization.	Assumptions based on the fact that survey mobilization allow to visit more sites than inspection mobilization.	Low
	Number of equipment pieces surveyed by site	Number of elements inspected on the same site.	Assumed same as number of equipment pieces during inspection +1.	Low
	Survey time per equipment	Time required for the survey of 1 equipment piece.	Service providers. Only given for wells and assumed similar for all equipment types.	Medium
	Allocation of mobilization to survey	Share of the vessel mobilization dedicated to leak survey. If other activities are performed such as bathymetry measurements, the share is less than 100%.	Interviews with operators.	Medium
	Share of detection during survey	% of the equipment pieces surveyed that need to be inspected as a follow up	Interviews with operators, rough estimate.	Low
Leak quantification	Rate estimation time	Time on the spot required for the estimation of the rate of 1 leak (typically by bubble count or	Service providers.	High

Systems	Parameter	Description	Source	Confidence
		displaced volume type measurement).		
	Sampling time	Time on the spot required to collect the gas coming from 1 leak (for analysis).	Service providers.	High
Leak repair	Repair time	Time on the spot required to repair 1 leak.	Service providers and interviews with operators. Few data points due to small number of cases and variability.	Medium
	Allocation of mobilization to repair	Share of the vessel mobilization dedicated to leak repair. If other activities are performed on the spot such as cleaning or inspection, the share is less than 100%.	Service providers and interviews with operators.	High

For each parameter, 3 values have been collected: a default value, a minimum value and a maximum value. The minimum and maximum values reflect the extreme situations that can be encountered depending on operating and geographical conditions. Therefore, a large range does not necessarily mean that the quantification of the parameters is uncertain, but rather that there is a large variability in the reality of the activities. For parameters estimated by operators or service providers, the default value is the most typical value. For parameters derived from the analysis of facilities and well datasets, the default value is the average value.

Data regarding equipment inspection and leak quantification have a medium to high level of confidence due to specific inputs from service providers. Based on their experience, they provided minimum, default and maximum values for each parameter, differentiated by depth and equipment when relevant.

It should be noted that the ranges of time (inspection, leak rate estimation, gas sampling) are not measured but are the best estimates of the service providers.

Data regarding distances and number of sites are associated with a medium to high level of confidence. Indeed, the analysis of the datasets published by Sodir allows to derive numbers that are representative of the average distances for installations on the Norwegian continental shelf. The service providers also shared information regarding distances and number of sites derived from their record of activities on some specific mobilizations.

Data regarding equipment surveys have a medium to low level of confidence due to some key parameters being based on assumptions derived from interviews with operators.

Data regarding leak repair have a medium level of confidence. Indeed, operators and service providers agree that subsea equipment leaks are rare and, that, when a repair is needed, the duration of the repair activities varies greatly depending on the type of equipment, type of damage, magnitude of the leak and environmental conditions. Therefore, the range given for the repair time is large to reflect the variety of situations, but the default case cannot be qualified as "typical".

The default case should be considered as a theoretical scenario where all parameters are set to an average value. The reader is invited to consider the ranges of values used for each parameter, to assess how the results best apply to a given situation.

Vessel and ROV

Information regarding the types of vessels and ROV used during LDAR campaigns was given by operators and service providers and was completed by information found on the websites of several vessel providers. Two main types of vessels are used: the Inspection, Maintenance and Repair (IMR) vessels, and the Platform Supply Vessels (PSV). The vessels examined in this study varies in deadweight between 2900 and 7200 tons and in length overall between 73 and 113 meters. The vessels use different types of fuels: liquefied natural gas (LNG), marine diesel oil (MDO) and marine gas oil (MGO). The vessels differ in speed and fuel consumption, with IMR vessels consuming more than PSV.

To explore the impacts of the choice of vessel on the carbon footprint of subsea LDAR, four vessel categories have been studied and are summarized in Table 5.

Table 5 – Characteristics of the vessels considered for the assessment

Vessel category	Vessel type	Fuel	Source of the information	Differentiation traveling and dynamic positioning
IMR – MDO – medium consumption	IMR	MDO	Information about 1 vessel given by 1 service provider + Information about 1 vessel on provider's website.	No – lack of information
IMR – MDO – high consumption	IMR	MDO	Information about 1 vessel on provider's website.	No – lack of information
PSV – MGO – average consumption	PSV	MGO	Average of information for 3 vessels on provider's website	Yes
PSV – LNG – default	PSV	LNG	Information about 1 vessel given by 1 service provider	Yes

For each vessel category, the economic speed and the fuel consumption were collected. When available, the fuel consumption at economic speed and the fuel consumption during dynamic positioning were differentiated. In the default case, the "IMR – MDO – medium consumption" vessel is used because operators mentioned IMR vessels as being the most used and because it is a conservative assumption, IMR vessels having a higher consumption than PSV in average.

The type and weight of two ROV used during subsea LDAR campaigns are indicated by service providers. The ROV uses electricity which is produced onboard the vessel. It is assumed that electricity production

does not induce a significant increase in fuel production during operations compared to the fuel used for the dynamic positioning system.

Emission factors

Direct emissions due to fuel combustion are taken from the greenhouse gas study of the International Maritime Organization[27]. This report gives the amount of different gas emitted per ton of MDO and LNG combusted. This is converted into kilograms of carbon dioxide equivalent (kg CO_2e) using the global warming potential at 100 years indicated by the IPCC.[28] Emission factor for MGO is assumed to be the same as for MDO.

Emissions due to the value chain of fuel are estimated using emission factors taken from the database ecoinvent 3.9. These emission factors quantify emissions during the extraction, processing and transport of the fuels.

Emissions due to the vessel life cycle are quantified using an emission factor for a barge tanker taken from ecoinvent 3.9. To be conservative, the emission factor is scaled proportionally using the deadweight of the vessel. The lifetime of the vessel is assumed to be 20 years.

Emissions due to the ROV life cycle were quantified in openLCA using emission factors taken from ecoinvent 3.9 by making rough assumptions on the material composition of the ROV. The lifetime of the ROV is assumed to be 10 years.

Emissions from the fuel value chain, from the vessel lifecycle and from the ROV lifecycle are classified as indirect emissions.

Emission factors related to fuel consumption have a high level of confidence as they are specific to the type of fuel, to the sector (combustion in the maritime sector) and to the geography (value chain for use in Europe or, where available, in Norway). On the other hand, emission factors related to the vessel and ROV life cycles have a low level of confidence but are conservative. As the analysis shows that the vessel and ROV life cycle emissions are negligible compared to emissions related to fuel consumption (about 1% of the total footprint), refining these emission factors would not impact the results and conclusions.

2.5 Geography and time coverage

The results of the study reflect the LDAR practices of operators on the Norwegian continental shelf:

- Operators interviewed operate at a variety of latitudes and at various distances from shore along the Norwegian continental shelf. However, not all operators present in Norway were interviewed.
- The datasets published by Sodir have been filtered to retain all but only the facilities and wells on the Norwegian continental shelf.

Even though the ranges collected for each parameter are meant to encompass a variety of operating conditions, this study does not claim to be exhaustive of all possible situations that can be encountered on the Norwegian continental shelf. The coverage is notably limited by the number of service providers that have given a positive response in the data collection phase. Exhaustiveness could be improved by obtaining data from more service providers and including several teams within each service provider (as one team may operate on a limited number of fields).

The results of the study reflect the LDAR practices in 2024:

[27] International Maritime Organization, "Fourth IMO GHG Study 2020", 2020. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

[28] C. Smith et al. "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material". In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* 2021. Available from https://www.ipcc.ch/.

- Information given by operators is based on their experience in the recent past years.
- Information given by service providers is based on their experience in the recent past years and specific campaigns carried out in 2023-2024
- The datasets published by Sodir contain data updated in 2024 for the year 2023

No assumption was made regarding the evolution of technologies such as, for example, the improvement of vessel engines, the use of alternative fuels or the deployment of new detection or repair methods.

3 Life cycle inventory

The values of the parameters used to calculate the activity data are shown in Table 6. Inspection time is differentiated by equipment type. The number of wells inspected on the same site varies from 1 for single well templates to 8 for multi-well templates. The calculated average considering all templates is 3.3 and is assumed independent of the status of the well. For other equipment, it is assumed that only 1 piece is inspected per site. In practice, several risers may be inspected during the same campaign if they are co-located at a host facility. No specific information on the average and maximum number of risers or manifolds inspected was available during the data collection so only the conservative assumption that 1 piece is inspected at a time was retained.

All other parameters are independent of the type of equipment. Distances are estimated using information on wells only but are deemed applicable to other equipment as manifolds and risers are located on the same location as or close to wells. Contrary to equipment inspection, the number of equipment pieces surveyed, and the survey time are assumed independent of the type of equipment, as the MBES can survey all equipment in the area.

The allocation of mobilization to inspection, survey or repair is set to 100%. This reflects the conservative assumption that leak detection (respectively repair) is the main reason for deploying the vessel during leak detection (respectively repair) campaign – though potentially other activities could be added to optimize scheduling and resources. In practice, other activities may be carried out during the same mobilization such as cleaning and maintenance (in parallel to inspection), repairs, bathymetric measurements (in parallel to survey). An arbitrary value of 50% is considered for the minimum value to discuss the sensitivity of the results to this model assumption and the consequences of different LDAR planning. For equipment inspection and leak repair, it is assumed that other activities may be carried out during the same vessel mobilization, but not simultaneously to the inspection or repair. For equipment survey, other activities may be carried out at the same time when the vessel travels at reduced speed on the site.

Table 6 – Default, minimum and maximum values of the parameters used to calculate the carbon footprint of equipment inspection, equipment survey, leak quantification and leak repair.

Parameter	Equipment	Unit	Default value	Minimum value	Maximum value
Distance between sites	All	km	2.7	0.1	13
Distance quayside - site	All	km	145	47	290

Parameter	Equipment	Unit	Default value	Minimum value	Maximum value
Distance demobilization site - quayside	All	km	0 [29]	31	1096
Number of sites inspected	All	-	13	1	30
Number of equipment pieces inspected by site	Wells	-	3.3	1	8
	Other[30]	-	1	1	1
Inspection time per equipment	Active wells – shallow water	h	4	2	6
	Active wells – deep water	h	6	2.5	9
	Temporarily abandoned wells – shallow water	h	2	1	3
	Temporarily abandoned wells – deep water	h	2.5	1.5	4
	Manifolds	h	5.5	2	10
	Risers and riser bases	h	4.5	1.5	8
Allocation of mobilization to inspection	All	%	100%	50%	100%
Number of sites surveyed	All	-	20	10	40
Number of equipment pieces surveyed by site	All	-	4.3	1	9
Survey time per equipment	All	h	0.22	0.15	0.29
Allocation of mobilization to survey	All	%	100%	50%	100%

[29] The distance from demobilization site to quayside is excluded from the system boundaries. Values were collected to assess the sensitivity of the results to this model assumption.
[30] Conservative estimates due to lack of data availability.

Parameter	Equipment	Unit	Default value	Minimum value	Maximum value
Share of detection during survey	All	%	30%	10%	50%
Rate estimation time[31]	All	h	2	0.5	5
Sampling time	All	h	2	1	3
Repair time	All	h	72	8	240
Allocation of mobilization to repair	All	%	100%	50%	100%

Source: Carbon Limits, based on information provided by operators, service providers and information extracted from Sodir's datasets, 2024

4 Impact assessment and results interpretation

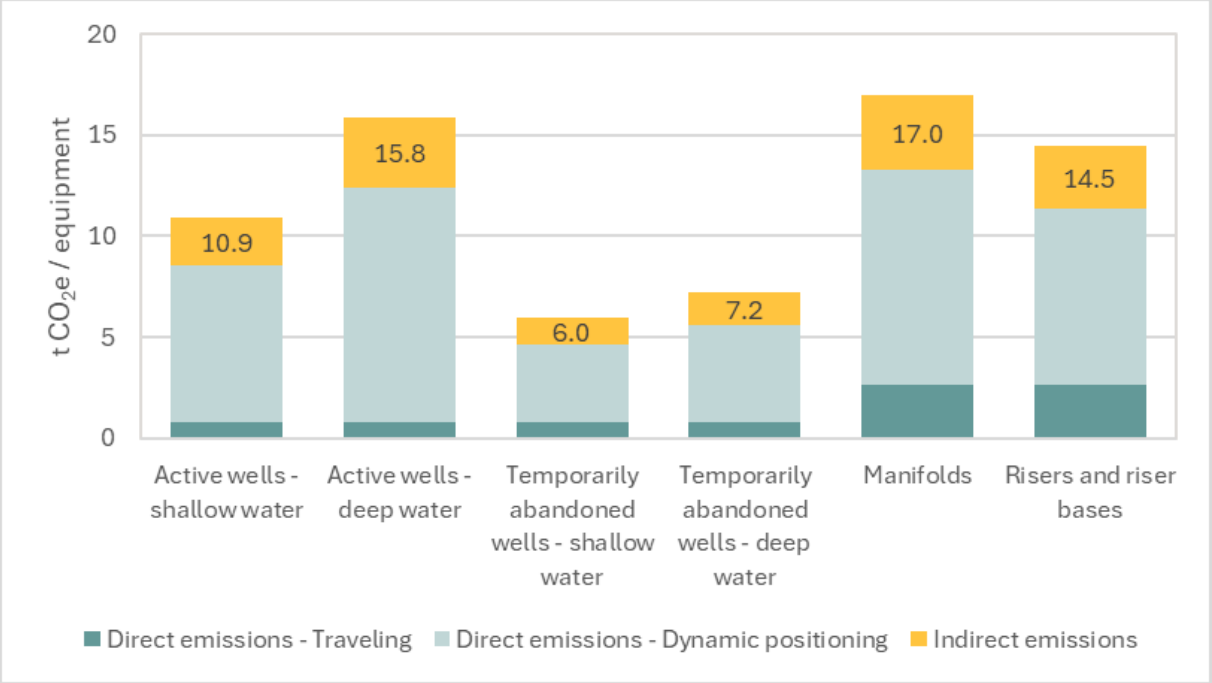
The results for the carbon footprint assessment of the four systems under default assumptions (default values for each parameter) are presented in sections 4.1 to 4.3 below. An explanation of the results by scope is given in section 4.4. The sensitivity of the results to the different parameters is detailed in section 4.5, using the range of values displayed in Table 6. Finally, in section 4.6, results are discussed with respect to the requirements set out in the EU regulation, in terms of frequency, repair limit, quantification requirements and repair delays.

4.1 Equipment inspection

Figure 6 shows the carbon footprint of equipment inspection by equipment type.

[31] In the model, it is assumed that leak quantification requires some set-up after leak detection: to retrieve the tools from the vessel and to wait for stabilization of the environment. If the right tool is readily available in the ROV used for detection and that the size leak matches the optimal conditions for the tool (*e.g.*, bottle size), the sampling and rate estimate time may be shorter.

Figure 6 - Carbon footprint of equipment inspection - Emissions per scope



Source: Carbon Limits analysis, 2024

The carbon footprint for active wells in shallow water is 10.9 tCO_2e / well, meaning that inspecting one active well in shallow water one time leads to emissions equal to 10.9 tCO_2e / well.

The carbon footprint of well inspection ranges from 6.0 to 15.8 tCO_2e / well. Inspection of wells in deep water requires more time than in shallow water thus resulting in a higher carbon footprint. Inspection of temporarily abandoned wells may take less time than active wells, because part of the equipment may have been removed. Consequently, at similar depth, the carbon footprint of temporarily abandoned wells is lower than the one of active wells.

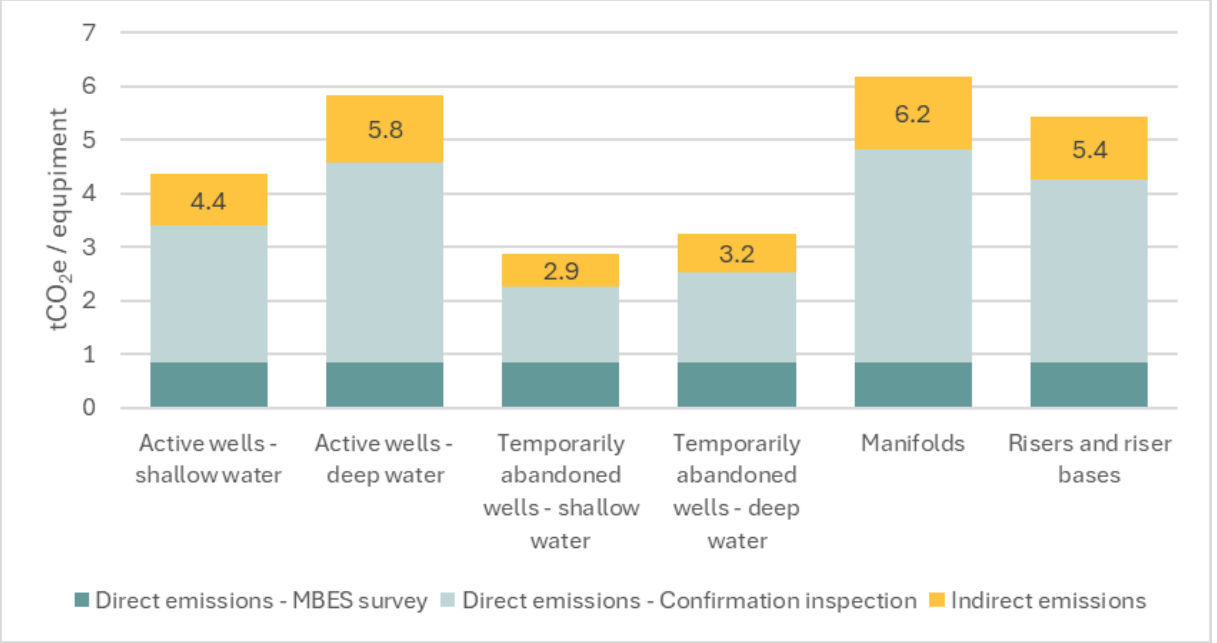
The carbon footprints of inspection for manifolds and risers (and riser bases) are respectively 17.0 and 14.5 tCO_2e / equipment. Direct emissions due to fuel combustion during travel to site represent a higher share of the footprint than for wells (up to 18%). This is because only 1 manifold or riser is inspected per inspection site, while 3.3 wells are inspected per site on average.

For all equipment types, the most significant share of the carbon footprint comes from the time spent onsite for the inspection, which accounts for between 60-73% of the total emissions. Indirect emissions (emissions due to the value chain of fuel and to the vessel and ROV lifecycles) account for 22% of the carbon footprint of inspection for all equipment types.

4.2 Equipment Survey

The carbon footprint of equipment survey ranges from 2.9 to 5.8 tCO_2e / equipment for wells. For manifolds and risers, the footprint amounts to 6.2 and 5.4 tCO_2e / equipment.

Figure 7 - Carbon footprint of equipment survey - Emissions per scope



Source: Carbon Limits analysis, 2024

During the MBES survey, the time per equipment pieces is assumed to be independent from the equipment types as all elements in the survey area are screened simultaneously. Therefore, the direct emissions due to fuel combustion during the survey are the same for all equipment types (0.8 tCO_2e / equipment). The difference between equipment types arises due to the confirmation inspection after detection. The time needed to survey one piece of equipment is short compared to the time needed for inspection. For instance, for temporarily abandoned wells, survey time is 0.22 hours and inspection time is 2 hours. Therefore, direct emissions during inspection represent the largest share of the footprint, even if the confirmation inspection is only done on a share of the population of the equipment surveyed (30%).

For a same functional unit, the carbon footprint of equipment survey is lower than the one of inspection. However, this conclusion must be considered carefully because:

- the assessment of the carbon footprint of equipment survey relies on some parameters (share of detection, number of sites surveyed, number of equipment pieces per site) with very low confidence (See Section 4.5 for sensitivity analysis).
- The results are presented for default scenarios. The most effective detection method or combination of methods method may differ on a case-by-case basis. Comparable scenarios should be built at the field or group-of-fields scale to determine which method has the lowest footprint for one specific application.

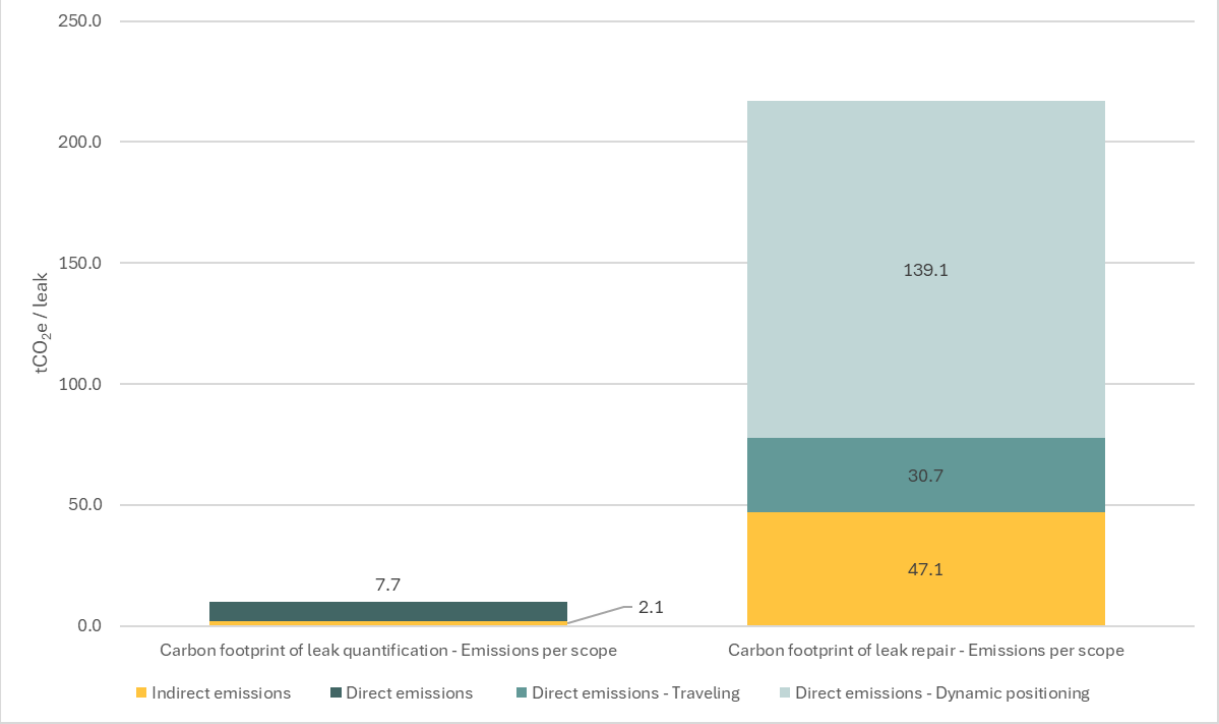
4.3 Leak quantification and repair

The carbon footprint of quantifying one leak (using bubble counts and resampling) is 9.8 tCO_2e / leak. The time needed to perform the leak rate estimation, and the time needed to perform gas sampling are both 2 hours. Therefore, the carbon footprint of leak quantification is split equally between the two activities. This means that if only one of the two activities is carried out, then the impact of the activity would be halved (4.9 tCO_2e/equipment instead of 9.8 tCO_2e/equipment).

The average carbon footprint of the leak repair results in 216.9 tCO_2e / leak. The dynamic positioning accounts for 64% of the carbon footprint of the leak repair, and the largest contributor to emissions. The

estimated time to perform the leak repair (72 hours), is significant compared to the time and associated emissions during travelling and other indirect emissions.

Figure 8 - Carbon footprint of leak quantification and repair based on direct and indirect emissions

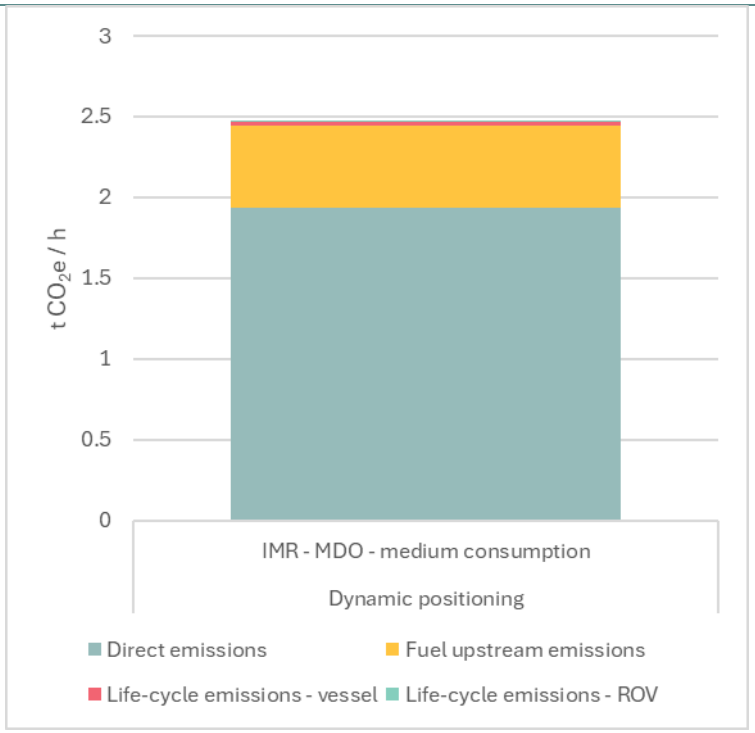


Source: Carbon Limits analysis, 2024

4.4 Emission Factors

Emissions are proportional to the time spent during operations, either traveling or during dynamic positioning, normalized by equipment or leak (see Section 2.4). Therefore, the split of emissions per scope are easily explained by looking at the emission factor per hour: consumption (kg fuel / h) x emission factor (tCO_2e / kg fuel).

Figure 9 - Emission factors per hour of operation



Source: Carbon Limits analysis, 2024

The emission factor per hour during dynamic positioning for the vessel considered in the default scenario is represented on Figure 9. 78% of the emission factor is due to direct emissions, while the remaining 22% is attributed to upstream impacts. 95% of the upstream impacts correspond to the emissions in the value chain of fuel production, while the remaining 5% are due to the life-cycle emissions of the vessel and ROV. This distribution of emission factors is consistent for all vessel types and fuels considered as part of the analysis.

Table 7 – Split of the emission factor per scope for the IMR vessel running on MDO (medium consumption)

Life cycle phase	Emission factors (t CO_2e / h)	Share of total emission factor
Direct emissions	1.9	78%
Indirect Emissions	0.5278	22%
Indirect - Fuel upstream emissions	*0.5*	*21%*
Indirect - Life-cycle emissions - vessel	*0.027*	*1%*
Indirect - Life-cycle emissions - ROV	*0.0008*	*0.03%*
Total	2.5	100%

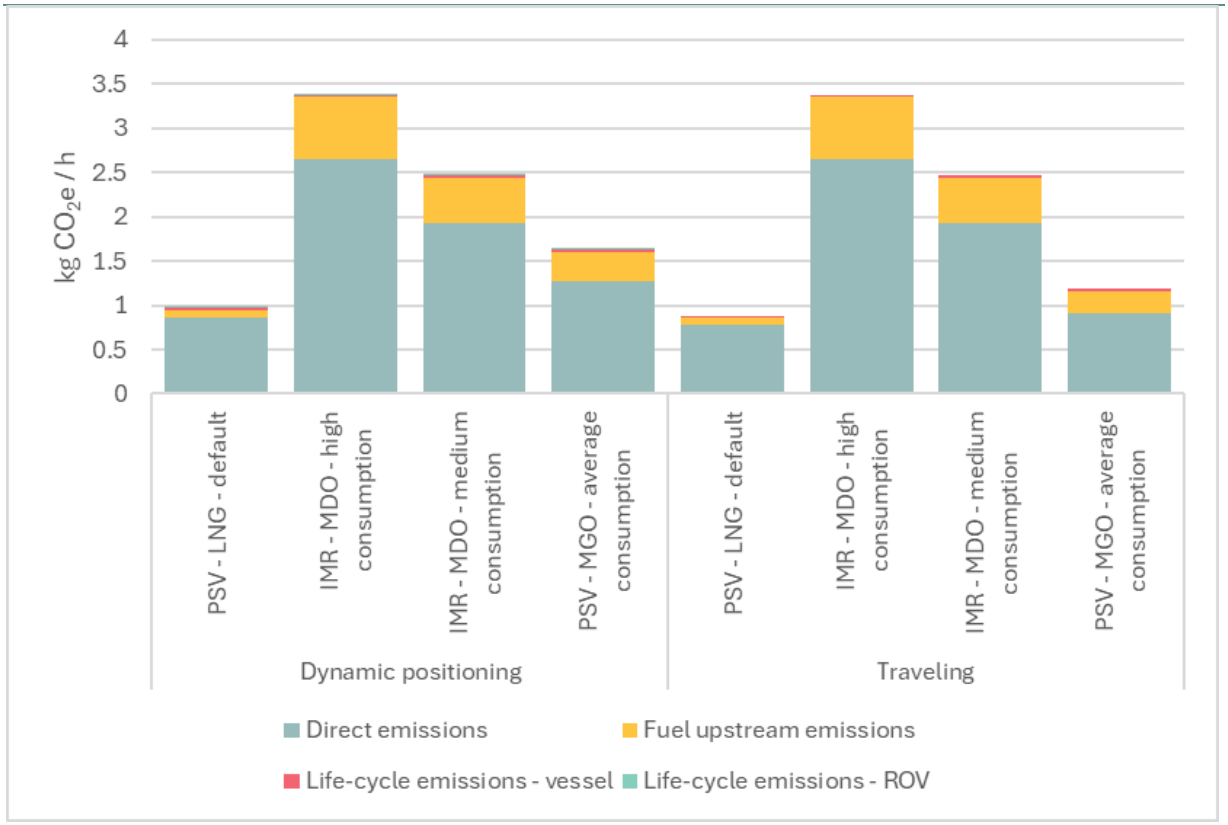
In the default case (IMR vessel running on MDO), the consumption data differentiated between traveling and dynamic positioning is not available. The emission factor on both phases is therefore considered to be the same. For vessels on which differentiated data was collected, the consumption in dynamic positioning is lower than during traveling.

4.5 Sensitivity Analysis

Impact of the type of vessel and fuel on the hourly emission factor

Figure 10 shows the emission factor per hour for the different vessels considered in this study.

Figure 10 - Sensitivity of the hourly emission factor to the vessel and fuel type



Source: Carbon Limits analysis, 2024

The hourly emission factor varies by - 64% / +31% when comparing the different vessels to the default case ("IMR – MDO – Medium Consumption" scenario)[32]. The "IMR – MDO – high consumption" results in the highest emission factor, both for dynamic positioning and traveling, while the "PSV – LNG – default" scenario results in the lowest. This is because LNG has lower upstream emissions than MDO/MGO. Direct emissions are similar for LNG and MDO/MGO.

For the PSV, data differentiated by phase was collected. Fuel consumption, and therefore the emission factor, is lower during dynamic positioning than during traveling.

As per operators' interviews, IMR vessels have been selected as the default assumption for LDAR operations. They are large vessels, compared to PSV, and therefore have larger emission factors.

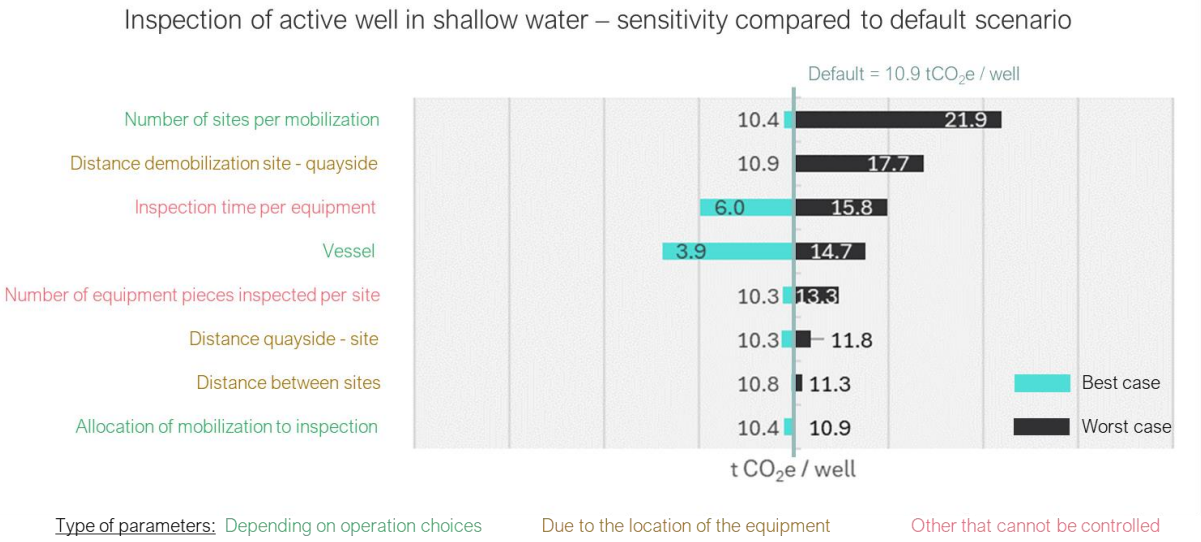
Only LNG and MDO vessels currently in use in Norway are included in this study: the use of alternative fuels or of combustion-improvement technologies is outside the scope of this analysis.

[32] As a reminder, IMR = Inspection, maintenance and repair (vessel), PSV = Platform supply vessel, MDO = Marine diesel oil, MGO = Marine gas oil, LNG = Liquefied natural gas

Equipment inspection – Sensitivity summary

Figure 11 presents the sensitivity of the carbon footprint of an inspection of an active well in shallow water based on various parameters. The vertical line represents the carbon footprint in the default scenario (10.9 tCO_2e / well). For each parameter (each row), the carbon footprint is calculated with the extreme values of the range, giving a worst case (in black) and a best case (in blue). Parameters vary one at a time, which means that this graph does not make appear the combined effects of some parameters (*e.g.,* number of sites and distance as shown on Figure 20). A detailed analysis by parameter is available in Appendix C.1.

Figure 11 – Maximum and minimum carbon footprint of equipment inspection (active well in shallow water) by variation of individual parameters. The middle vertical line corresponds to the default scenario.



Source: Carbon Limits analysis, 2024

The carbon footprint of equipment inspection can vary significantly with varying parameters. For example, the largest positive variation is observed for the number of sites inspected per mobilization: when a vessel only visits one site, the carbon footprint per well is doubled compared to the default case (13 sites). The results are thus sensitive to the way the inspection campaigns are planned. Fields with large number of sites may benefit from scale effect. This effect may however be limited when the operations (including transit) exceed a certain duration (*e.g.* fourteen days for a specific campaign), in which case several mobilizations are required to ensure crew rotation.

Similarly, the vessel type is a parameter that can be influenced by operators' or service providers' choice.[33] By selecting either a "PSV – LNG – default" vessel (best case) or a "IMR – MDO – high consumption" vessel (worst case), the carbon footprint per well deviates -63%/+35% from the default value.

The travel distance from demobilization site to quayside is not included in the system boundaries of the default scenario. However, the analysis shows that in the case of remote locations, the carbon footprint can increase up to 63% due to this parameter. On the other hand, given the ranges considered for the distance from quayside to site and between sites, the results do not deviate substantially from the default due to these parameters.

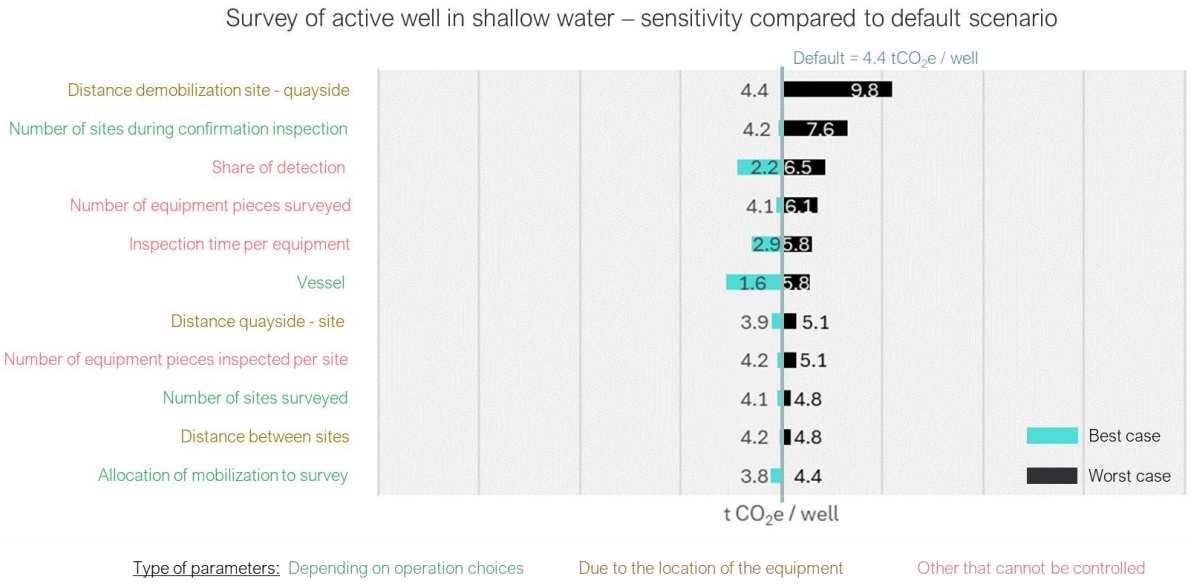
The results are also sensitive to the inspection time per equipment: with the range given, the carbon footprint varies between 6.0 and 15.8 tCO_2e / well.

[33] In practice vessel choice is limited by vessel availability and by the type of work to be carried out (different tools and capacity).

Equipment survey – Sensitivity summary

Figure 12 presents the sensitivity of the carbon footprint of a survey of an active well in shallow water based on various parameters. The middle bar represents the carbon footprint in the default scenario (4.4 tCO_2e / well). A detailed analysis by parameter is available in Appendix C.2.

Figure 12 - Maximum and minimum carbon footprint of equipment survey (active well in shallow water) by variation of individual parameters. The middle vertical line corresponds to the default scenario.



Source: Carbon Limits analysis, 2024

Like equipment inspection, accounting for the distance from demobilization site to quayside can increase substantially the carbon footprint of equipment survey in the most remote places. With a maximum distance of about 1,100 km, the carbon footprint of survey amounts to 9.8 tCO_2e / well.

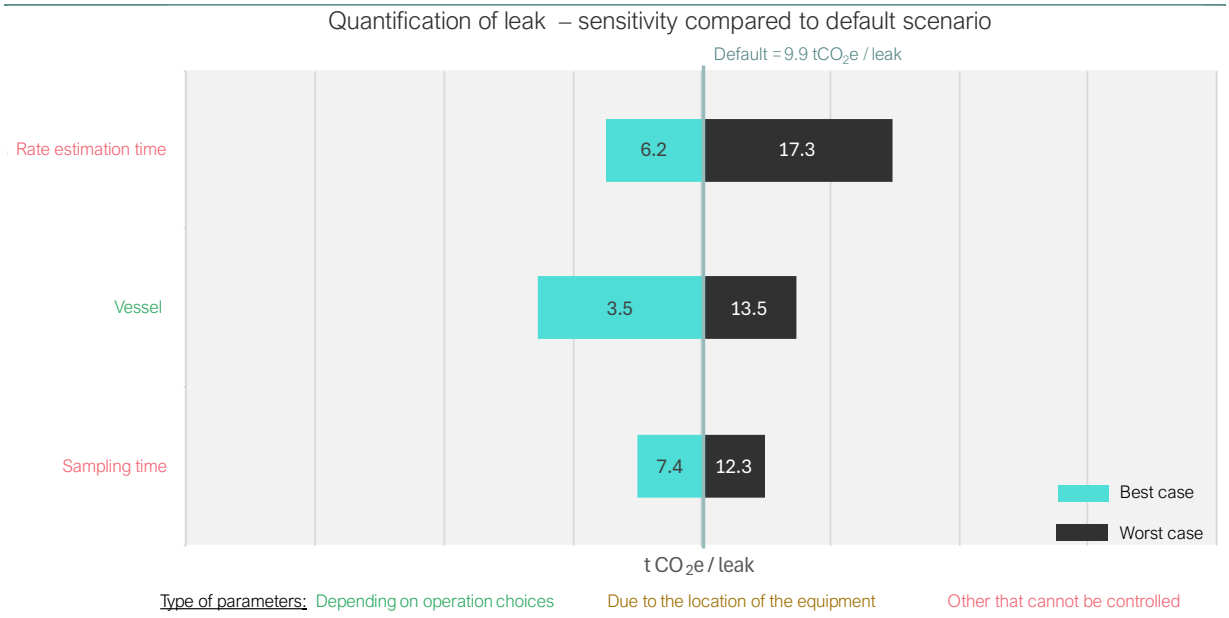
The carbon footprint can also increase by 33% or decrease by 64% depending on the vessel used for the survey and follow-up inspection. The carbon footprint also increases to 7.6 tCO_2e / well if, during the confirmation inspection, vessels are mobilized to inspect a single site at a time.

The carbon footprint of survey is very sensitive to parameters such as the share of detection and the number of equipment pieces surveyed which are parameters based on rough assumptions. This lowers the confidence of the results. Results could be refined with additional data collection.

Leak quantification – Sensitivity summary

Figure 13 presents the sensitivity of the carbon footprint of leak quantification based on various parameters. The middle bar represents the carbon footprint in the default scenario (9.9 tCO_2e / leak). A detailed analysis by parameter is available in Appendix C.3.

Figure 13 - Maximum and minimum carbon footprint of leak quantification by variation of individual parameters. The middle line corresponds to the default scenario.



Source: Carbon Limits analysis, 2024

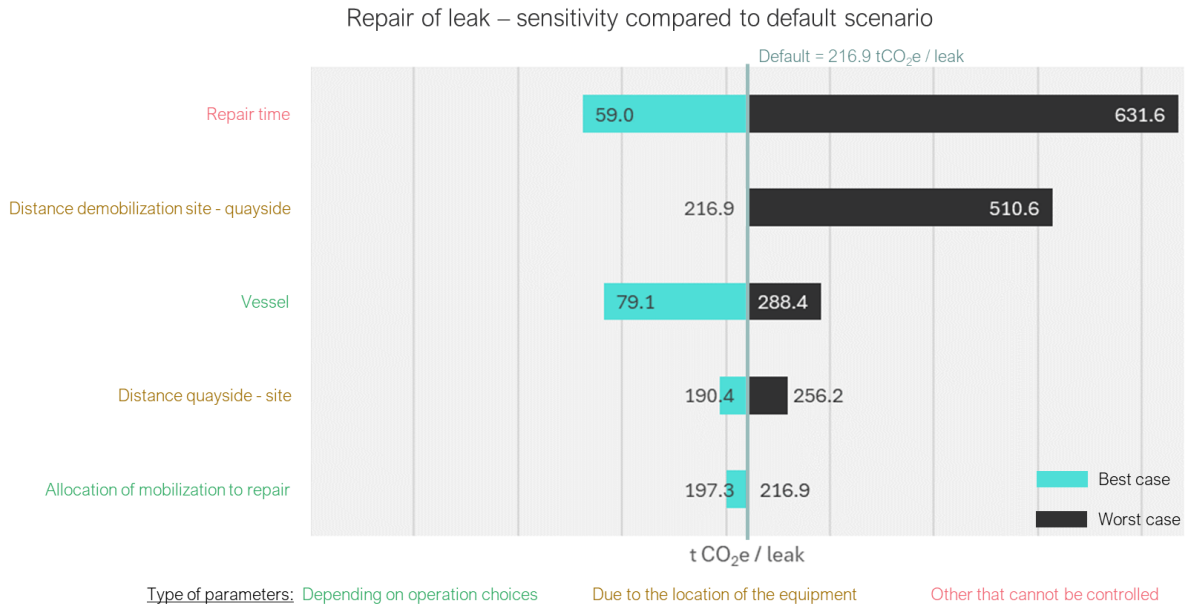
Leak rate estimation time and sampling time are two parameters that can vary depending on ambient conditions during the deployment. With the range of values indicated by service providers for rate estimation time, the carbon footprint of leak quantification varies -38%/+75% compared to the default scenario. With the ranges indicated for sampling time, the results vary ±25%.

By selecting either a "PSV – LNG – default" vessel (best case) or a "IMR – MDO – high consumption" vessel (worst case), this can result in a relative difference in carbon footprint of -64%/+37% from the default value.

Leak repair – Sensitivity summary

Figure 14 presents the sensitivity of the carbon footprint of leak quantification based on various parameters. The middle bar represents the carbon footprint in the default scenario (216.9 tCO_2e / leak). A detailed analysis by parameter is available in Appendix C.4.

Figure 14 - Maximum and minimum carbon footprint of leak repair by variation of individual parameters. The middle line corresponds to the default scenario.



Source: Carbon Limits analysis, 2024

The carbon footprint is most impacted by the repair time due to the very large range of repair time indicated by operators and service providers. This reflects the fact that there is no typical repair for subsea equipment.

As for the other systems, changing the assumption on the kind of vessel used can increase (respectively decrease) the carbon footprint of repair by 33% (respectively 64%). Larger repairs are more likely to be done with larger vessels (IMR vessels) and are therefore associated with higher fuel consumption. In the event of plugging and abandonment or replacements, extensive resources are required and can exceed the maximum value considered as part of this study.

As previously discussed for equipment inspection and survey, accounting for distance from demobilization site to quayside can increase significantly the carbon footprint of repair for remote locations (+ 135% with the longest distance). The distance from quayside to site impacts more the results than for equipment inspection based on the assumption that the vessel is mobilized for the leak repair only.

4.6 Carbon Footprint of LDAR practices in scenarios as per the EU Methane Regulation

In this section, results are expressed as equivalent of leak rates to discuss the implications of the EU Regulation in terms of LDAR frequency, repair limit and quantification obligations. As a reminder, this study only quantifies greenhouse gas emissions due to conducting the inspection, survey, quantification and repair. The emissions due to the leak themselves, and therefore the total net emissions are not quantified. For instance, increasing the inspection frequency means that more inspections are carried out and therefore more emissions are caused by the inspections. But simultaneously, if a leak appears, more inspections means that the leak is more likely to be discovered faster and fixed faster. Hence, more frequent inspections can decrease emissions due to the leaks, but this effect is not studied here. **Therefore, this study should not be used on its own to derive optimum frequencies in terms of net emissions.**

The discussion is based on the default scenarios developed for the study. To explore the full range of results, a high and a low scenario are displayed on the figures and tables. These scenarios represent extreme situations when all parameters take the most favorable (low scenario) and the most unfavorable (high scenario) values of the range given by Table 6.

Equipment inspection

To account for different inspection frequencies, the carbon footprint of equipment inspection is expressed as an emission rate of methane-equivalent per hour that would occur continuously during the period between 2 consecutive inspections:

$$Carbon\ footprint\ [gCH4e/h] = \frac{Carbon\ footprint[tCO2e/equipment] \times 10^6[g/t]}{GWP_{CH4}\left[\frac{kgCO2e}{kgCH4}\right] \times Frequency[years] \times 8760[h/years]}$$

This unit is equivalent to the one of a methane leak, except that it represents emissions to air and not emissions to water. Indeed, only a share of the methane emissions emitted under water reaches the surface.

The carbon footprint of equipment inspection depending on the time between two inspections is represented on Figure 15 for wells in shallow water, on Figure 16 for wells in deep water and on Figure 17 for manifolds and risers.

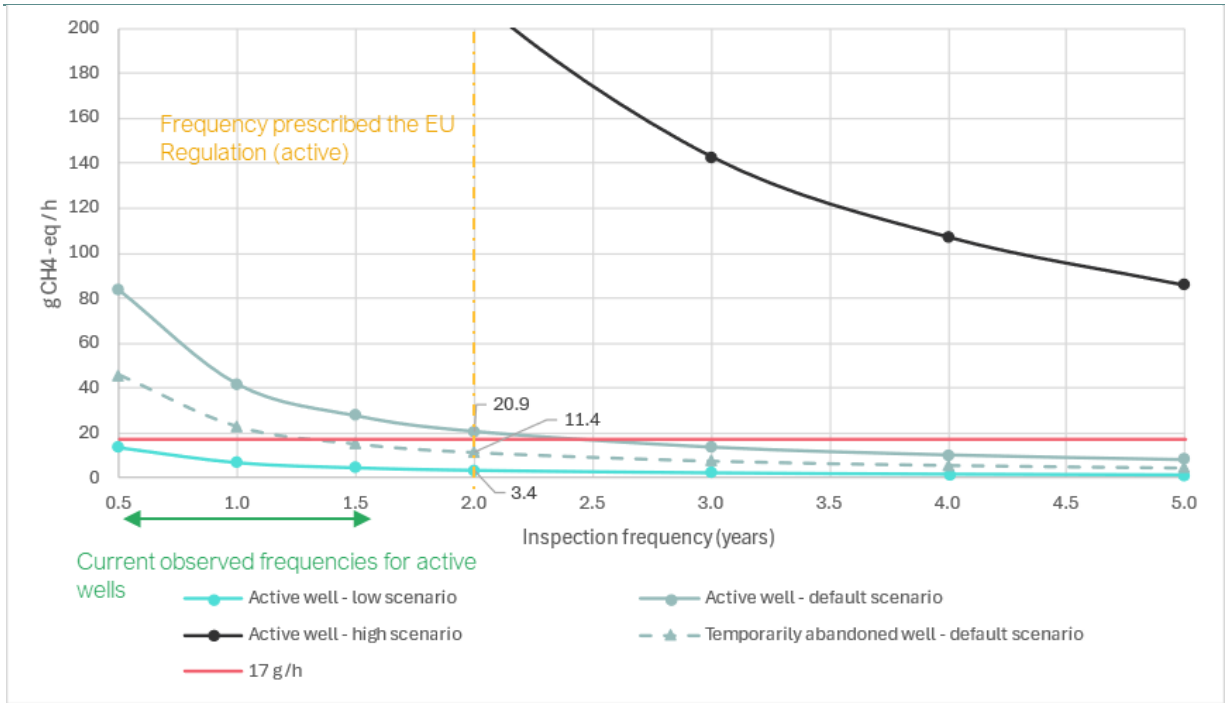
The results are compared with the repair limit set in the EU regulation of 17 gCH_4 / h to water. Therefore, a line at 17 gCH_4 / h to air is plotted on the graphs. This represents the most conservative case where all methane reaches the surface. In practice, a study by SINTEF found that 57 to 68% of methane released at 50-meter depth reaches the surface. For releases deeper than 360 meters, less than 1% of the methane reaches the surface.[34] Therefore, subsea leak rates must be larger than atmospheric leak rates to lead to the same greenhouse gas emissions to air. For example, assuming a transport of 68%, a leak of 17 gCH_4/h directly to air would be equivalent to a leak of 24.6 gCH_4 / h to water at 50-meter depth.[35]

The results expressed in leak rate equivalent are sensitive to the metric used for converting $kgCO_2e$ to $kgCH_4$ (GWP_{CH4}). If the GWP at 20 years of methane is used instead of the GWP at 100 years, the leak rate equivalent is divided by 2.8.

[34] O. G. Brakstad et al. "Oxidation of methane in seawater. Laboratory experiments and the use of models". Report OC2022 A-114. SINTEF. [Online] https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3038685. Note that the numbers presented in this section were communicated by Offshore Norge, based on an updated version of the report, yet to be published at the time of this study.

[35] 24.6*0.68 + 24.6*(1-0.68)*1/29.8=17 – with a conservative assumption that methane dissolved as CO_2 in water has a GWP of 1 as it has in air.

Figure 15 - Carbon footprint of shallow water well inspection compared to methane emissions to air based on inspection frequency



Source: Carbon Limits analysis, 2024

Inspection of active wells every 2 years, the minimum frequency prescribed by the EU Regulation, leads to a carbon footprint equivalent to the emissions to air of 21 gCH_4 / h for shallow-water wells and 30 gCH_4 / h for deep-water wells. This means that inspecting one active well in shallow water every 2 years leads to the same emissions as a subsea leak continuously emitting at a rate of 21 gCH_4 / h, assuming a 100% transport of methane to the surface, or of 36 gCH_4 / h assuming a 57% transport to the surface.[36]

In Norway, active wells are generally inspected every year (according to operators' interviews, between 0.5 and 1.5 year) which is equivalent to continuous emissions to air at a rate of 42 gCH_4 / h for shallow-water wells and 60 gCH_4 / h for deep-water wells.

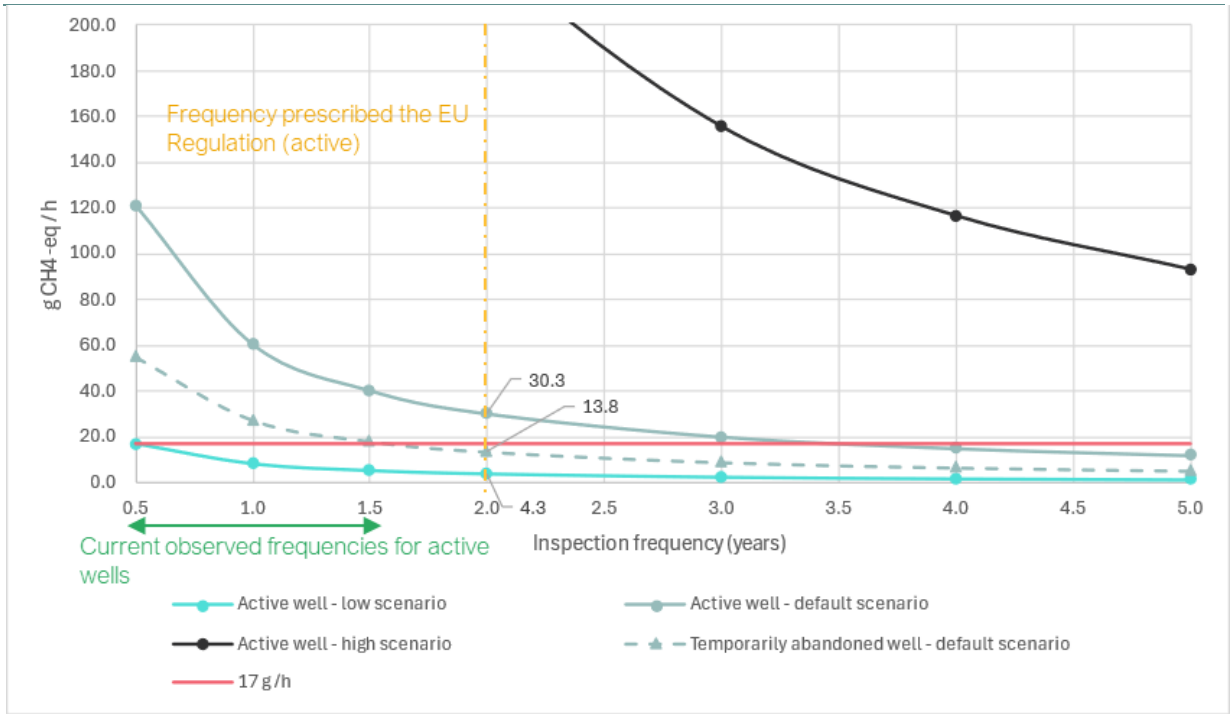
The carbon footprint of yearly inspections of temporarily abandoned wells is equivalent to continuous emissions to air at a rate of 23 gCH_4 / h for shallow-water wells and 28 gCH_4 / h for deep-water wells. Temporarily abandoned wells are currently inspected annually as per the Norwegian regulation.

For inspections of other equipment types, notably manifolds and risers, current inspection frequencies vary. Operators report inspection frequency between 1-3 years for risers and riser bases, while manifolds are inspected at frequencies ranging from every 2-5 years (observed frequencies due to risk-based approach).

At the minimum inspection frequency of 2 years prescribed by the EU Regulation, the carbon footprint of equipment inspection is equivalent to the emissions to air of 32 gCH_4 / h for manifolds, and 28 gCH_4 / h for risers and riser bases. Considering an inspection frequency of three years, the carbon footprint would be 21 gCH_4 / h for manifolds, and 19 gCH_4 / h for risers and riser bases. This means that the difference between inspecting manifolds every 2 or every 3 years is equivalent to a subsea leak continuously emitting at a rate of 11 gCH_4 / h, assuming a 100% transport of methane to the surface, or of 19 gCH_4 / h assuming a 57% transport to the surface.

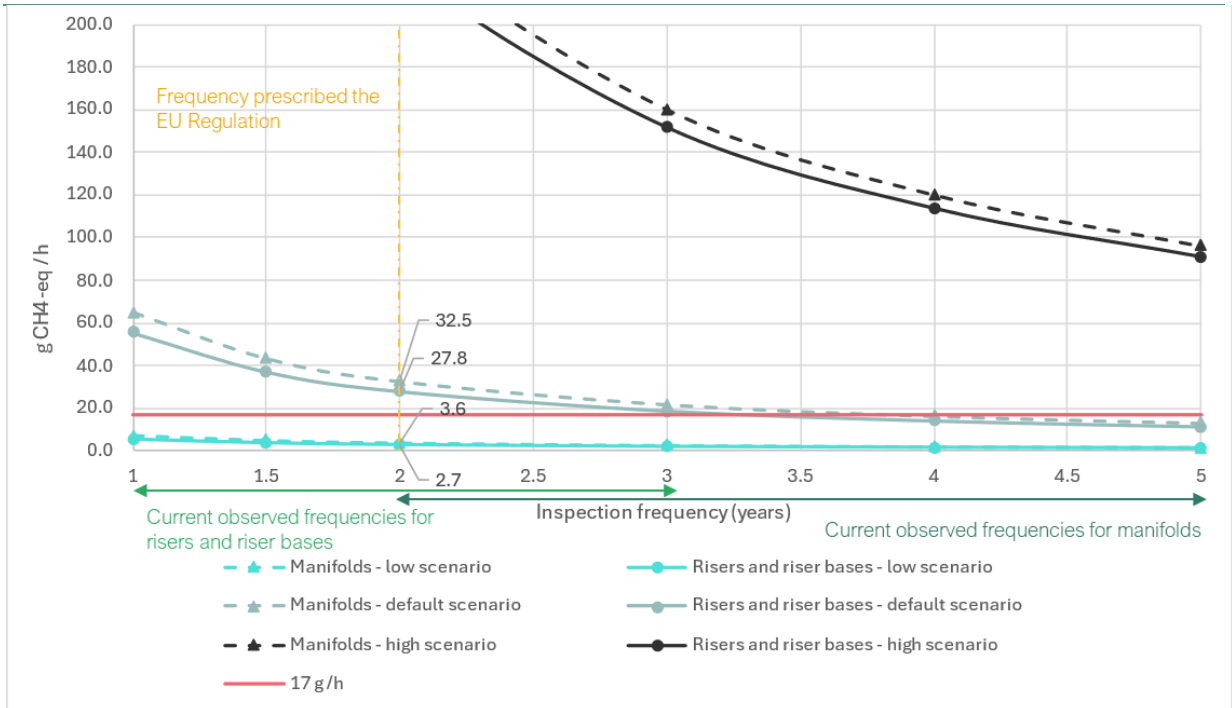
[36] The 57% transport share is illustrative. This parameter varies significantly with the water depth, even within the range considered for shallow wells (50 to 200 m).

Figure 16 - Carbon footprint of deep water well inspection compared to methane emissions to air based on inspection frequency



Source: Carbon Limits analysis, 2024

Figure 17 - Carbon footprint of inspection frequency based on inspection frequency compared to methane emissions for various equipment types



Source: Carbon Limits analysis, 2024

Leak quantification

In the default scenario, the carbon footprint of a leak quantification is 9.9 tCO_2e. To put this number in perspective, Table 8 shows how long it would take for a leak to have an equivalent climate impact, at different leak rate. A carbon footprint of 9.9 tCO_2e represents a continuous emission to air of 500 gCH_4 / h for 27 days or 15 $kgCH_4$ / h over a 22-hour period.

As leak quantification is not systematic in current practices in Norway, the quantification requirement of the EU Regulation could add a net impact of 9.9 tCO_2e per leak, assuming that both leak rate estimation and gas sampling are necessary.

Table 8 – Carbon footprint of leak quantification expressed as a leak duration for different leak rates (emissions to air).

	Default scenario	Low scenario	High scenario
tCO_2e / leak	9.8	1.3	27
Equivalent to (emissions to air):			
17 gCH_4 / h	812 days	109 days	6 years
500 gCH_4 / h	27 days	4 days	76 days
15 $kgCH_4$ / h	22 hours	3 hours	61 hours

Source: Carbon Limits analysis, 2024

Leak Repair

In the default scenario, the carbon footprint of a leak quantification is 217 tCO_2e. To put this number in perspective, Table 9 shows how long it would take for a leak to have an equivalent climate impact, at different leak rate. A carbon footprint of 217 tCO_2e represents a continuous emission to air of 500 gCH_4/h for 607 days or 15 $kgCH_4$/h over a 20-day period.

In the default and high scenarios, the whole vessel mobilization is allocated to the leak repair (no other activities, only 1 repair). This may typically be the case if repairs need to be done in a short period after detection.

The analysis indicates that vessel mobilization for the fix of individual small leaks might lead to more climate impact than the leaks themselves. For instance, in the default scenario, the direct emissions due to travel to site only amount to 30.7 tCO_2e (see bar chart on right side of Figure 8). This is equivalent to 7 years of continuous emissions to air at a rate of 17 gCH_4 / h, or 19 years at a rate of 6.3 gCH_4 / h. Therefore, having a longer repair delay might result in lower emissions if it makes it possible to combine the repair with other activities. For example, if a leak emits 17 gCH4 / h, repairing it during the next equipment inspection, after 2 years, leads to a smaller impact than mobilizing rapidly a vessel for repairing this unique leak. This conclusion cannot be generalized and should be assessed on a case-by-case basis depending on the size of the leak and the different operating parameters influencing the carbon footprint of the repair operations.

It is important to note that the interpretation of the scenarios in equivalent of emission rate to air must be done carefully because one of the main differences between the scenarios is the time needed for the repair. It can be expected that, to a certain extent, small leaks take less time (therefore leaning towards the low scenario) than larger leaks. However, the link between leak size and repair has not been quantified as part of this study.

In addition, the carbon footprint was estimated based on past experiences of operators and service providers. However, new repair technologies are developing and may be implemented in the future. Some local fixes may be possible with those technologies, requiring less time, especially for small leaks.

Table 9 - Carbon footprint of leak repair expressed as a leak duration for different leak rates

	Default scenario	Low scenario	High scenario
tCO_2e / leak	217	9.6	708
Equivalent to (emissions to air):			
17 gCH_4 / h	49 years	2 years	160 years
500 gCH_4 / h	607 days	27 days	5 years
15 $kgCH_4$ / h	20 days	21 hours	66 days

Source: Carbon Limits analysis, 2024

5 Conclusion

The carbon footprints of subsea equipment inspection, equipment survey, leak quantification and leak repair were calculated including direct emissions from fuel combustion while traveling and during dynamic positioning, indirect emissions due to the fuel value chain and indirect emissions due to the life cycle of the vessel and ROV. Emissions due to fuel represent 99% of the carbon footprint, with 22% of it coming from the fuel value chain.

Equipment inspection and equipment survey aim at detecting potential leaks. The carbon footprint is calculated for one inspection of one piece of equipment depending on the type of equipment:

Table 10 – Carbon footprint of equipment inspection and equipment survey per equipment type

	Active wells – shallow water	Active wells – deep water	Temporarily abandoned wells – shallow water	Temporarily abandoned wells – deep water	Manifolds	Risers and riser bases
Equipment inspection (tCO_2e / equipment)	10.9	15.8	6.0	7.2	17.0	14.5
Equipment survey (tCO_2e / equipment)	4.4	5.8	2.9	3.2	6.2	5.4

Source: Carbon Limits analysis, 2024

Equipment survey tends to have a lower carbon footprint than equipment inspection but the results for equipment survey have a low level of confidence as certain parameters are based on rough assumptions.

The carbon footprint of two activities taking place as part of LDAR activities after leak detection was also assessed:

- Leak quantification: 9.9 tCO_2e / leak
- Leak repair: 217 tCO_2e / leak

The carbon footprint of LDAR activities was assessed for typical (default) scenarios based on information collected from operators, service providers and NOD's datasets. However, results may vary significantly

based on field configuration, LDAR planning and ambient conditions. In particular, the mobilization of vessel for inspecting or surveying limited number of sites leads to a significant increase of the emissions per piece of equipment. The choice of vessel also impacts the results as they have different hourly fuel consumption: among the considered existing fleet, the PSV running on LNG lead to emissions 63% lower than the IMR vessel running on MDO. The analysis also showed that for the most remote locations, the travel of vessel from demobilization site to quayside can increase the carbon footprint of inspection by 63% and of repair by 135%, which highlights the importance to avoid single site visits.

Active and temporarily abandoned wells in Norway are already inspected with frequencies at least equal to the minimum frequencies prescribed by the EU Regulation. For manifolds and risers, setting fixed frequency of 2 years (3 years with relief) may increase the carbon footprint of inspection over time compared to the risk-based approach. The carbon footprint surplus can be quantified as leak-rate-equivalent which can be considered in further discussions in comparison with observable leak rates and probability.

In the event a leak is identified during inspection, the EU Regulation requires leak quantification, which results in additional climate impact of 9.9 tCO_2e / leak, assuming that gas sampling and leak rate estimation are carried out right after equipment inspection. Leak repair is mostly determined by the time needed for repair, which cannot be controlled and varies significantly depending on the type of repair and equipment.

However, the emissions due to travel to site alone can exceed the emissions due to the leaks themselves for leak rates around the repair limit indicated by the EU Regulation. For example, the carbon footprint of travel to site in the default scenario is 30.7 tCO_2e which is equivalent to 7 years of continuous emissions to air at a rate of 17 gCH_4 / h.

This study informs about the climate impact of carrying out LDAR depending on different conditions. It could be complemented by an analysis of the magnitude and occurrence of observed leaks to compare the results obtained to potential avoided emissions.

Annex A. Pipelines: parameters and preliminary results

Pipelines have been considered as an additional type of equipment but have been excluded from the scope of the study. The calculation model is not fitted for this type of equipment: as the length of pipeline may vary significantly, the time needed for inspection, survey or repair may also vary greatly. In addition, pipeline inspection can refer to inspection of the entire pipeline, or of sections thereof, or of components along the pipeline. Therefore, calculating the carbon footprint of LDAR per pipeline may lead to results that are not representative of actual practices.

This appendix presents some data regarding inspection and survey of entire pipelines that have been provided by operators and service providers. Preliminary results for the inspection of entire pipelines are also shown for information purposes. The calculation method and the data collection should be revised to obtain results with a sufficient level of confidence. More appropriate functional units could involve calculation of emissions per unit-length of pipeline or per equipment along the pipeline.

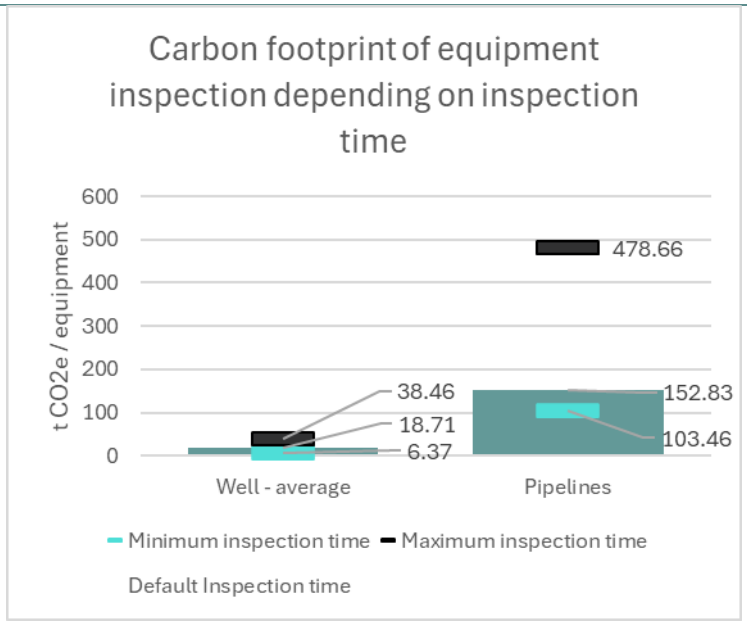
Table 11 – Values of model parameters collected or estimated for pipelines

Parameter	Unit	Default value	Minimum value	Maximum value
Number of sites inspected	-	1	1	5
Number of equipment pieces inspected by site	-	1	1	1
Inspection time per equipment	h	60	40	192
Number of sites surveyed	-	1	1	5
Number of equipment pieces surveyed by site	-	1	1	1
Survey time per equipment	h	1.58	1.36	33.6
Share of detection during survey[37]	%	17%		

Source: Carbon Limits, based on information provided by operators and service providers, 2024

[37] The modelling of follow-up inspection does not work for pipelines: instead of a number or a share of elements around which emissions are detected during the survey, what is needed is how long the pipeline inspection as a follow-up is compared to the inspection of the entire pipeline. This is a function of the number of potential leaking points encountered along the pipeline. Here it is assumed that thanks to the survey, the inspection only takes 10 hours instead of 60 (10/60=17%) because focused on special points.

Figure 18 – Preliminary results for the carbon footprint of pipeline inspection depending on the inspection time. Comparison with the carbon footprint of well inspection.



Source: Carbon Limits analysis, 2024

Annex B. Calculation model

In this section, the models used to calculate the carbon footprint of the different systems are detailed. As a reminder, the general method for calculation is:

$$Carbon\ footprint =$$

$$\left(Time_{Traveling} \times Fuel\ consumption_{Traveling} + Time_{DP} \times Fuel\ consumption_{DP}\right) \times Emission\ factor_{fuel}$$
$$+ \left(Time_{Traveling} + Time_{DP}\right) \times \left(\frac{Emission\ factor_{Vessel}}{Lifetime_{Vessel}} + \frac{Emission\ factor_{ROV}}{Lifetime_{ROV}}\right)$$

B.1 Equipment inspection

$$Time_{Traveling} = \frac{Allocation_{Insp}}{\#\ Equipment_{Insp} \times \#Site_{Insp}} \times \frac{D_{demob-quayside} \times 2 + D_{quayside-site} \times 2 + D_{site-site} \times \#Site_{Insp}}{Speed}$$

$$Time_{DP} = input\ parameter$$

Where:

Notation	Parameter	Unit
$Time_{Traveling}$	Time of travel allocated to the inspection of 1 piece of equipment	h / equipment
$Time_{DP}$	Time of dynamic positioning for the inspection of 1 piece of equipment	h / equipment
$Allocation_{Insp}$	Share of the vessel mobilization allocated to inspection (as opposed to other activities such as maintenance and cleaning)	%
$\#\ Equipment_{Insp}$	Number of pieces of equipment inspected in 1 inspection site	equipment / site
$\#Site_{Insp}$	Number of sites inspected during 1 vessel mobilization	site / mobilization
$D_{demob-quayside}$	Distance between the supplier's demobilization site and the quayside – Not included in default scenario	km
$D_{quayside-site}$	Distance between the quayside and the closest site	km
$D_{site-site}$	Distance between two successive sites that are inspected during the same vessel mobilization	km
$Speed$	Vessel speed	km / h

B.2 Equipment survey

$$Time_{Traveling} = Time_{Traveling-Survey} + Share\ detection\ \times Time_{Traveling-Insp}$$

$$Time_{Traveling-Survey} = \frac{Allocation_{Survey}}{\#\ Equipment_{Survey} \times \#Site_{Survey}} \times \frac{D_{demob-quayside} \times 2 + D_{quayside-site} \times 2 + D_{site-site} \times \#Site_{Survey}}{Speed}$$

$$Time_{DP} = Time_{DP-Survey} + Share\ detection\ \times Time_{DP-Insp}$$

$$Time_{DP} = input\ parameter$$

Where:

Notation	Parameter	Unit
$Time_{Traveling}$	Time of travel allocated to the survey (+ follow-up inspection) of 1 piece of equipment	h / equipment
$Time_{DP}$	Time of dynamic positioning for the survey (+ follow-up inspection) of 1 piece of equipment	h / equipment
$Time_{Traveling-Survey}$	Time of travel allocated to the survey of 1 piece of equipment	h / equipment
$Time_{Traveling-Insp}$	Time of travel allocated to the inspection of 1 piece of equipment. Calculated as in Section C.1.	h / equipment
$Time_{DP-Survey}$	Time of dynamic positioning for the survey of 1 piece of equipment	h / equipment
$Time_{DP-Inspc}$	Time of dynamic positioning for the inspection of 1 piece of equipment. Calculated as in Section C.1.	h / equipment
$Share\ detection$	Share of equipment surveyed for which a leak is detected and requires an inspection	%
$Allocation_{Survey}$	Share of the vessel mobilization allocated to survey (as opposed to other activities such as bathymetry measurements)	%
$\#\ Equipment_{Survey}$	Number of pieces of equipment surveyed in 1 site	equipment / site
$\#Site_{Survey}$	Number of sites surveyed during 1 vessel mobilization	site / mobilization
$D_{demob-quayside}$	Distance between the supplier's demobilization site and the quayside – Not included in default scenario	km
$D_{quayside-site}$	Distance between the quayside and the closest site. Same as for inspection.	km
$D_{site-site}$	Distance between two successive sites that are surveyed during the same vessel mobilization. Same as for inspection.	km
$Speed$	Vessel speed	km / h

B.3 Leak quantification

$$Time_{Traveling} = 0$$

$$Time_{DP} = Time_{Leak\ rate\ estimation} + Time_{Gas\ sampling}$$

Where:

Notation	Parameter	Unit
$Time_{Traveling}$	Time of travel allocated to the quantification of 1 leak	h / leak
$Time_{DP}$	Time of dynamic positioning for the quantification of 1 leak	h / leak
$Time_{Leak\ rate\ estimation}$	Time required for the estimation of the emission rate of 1 leak	h / leak

$Time_{Gas\ sampling}$	Time required for the sampling of 1 leak	h / leak

B.4 Leak repair

$$Time_{Traveling} = Allocation_{Rep} \times \frac{D_{demob-quayside} \times 2 + D_{quayside-site} \times 2}{Speed}$$

$$Time_{DP} = input\ parameter$$

Where:

Notation	Parameter	Unit
$Time_{Traveling}$	Time of travel allocated to the repair of 1 leak	h / leak
$Time_{DP}$	Time of dynamic positioning for the repair of 1 leak	h / leak
$Allocation_{Rep}$	Share of the vessel mobilization allocated to the repair of 1 leak (as opposed to other activities such as maintenance and cleaning, or other repairs)	%
$D_{demob-quayside}$	Distance between the supplier's demobilization site and the quayside – Not included in default scenario	km
$D_{quayside-site}$	Distance between the quayside and the closest site. Same as for inspection.	km
$Speed$	Vessel speed	km / h

Annex C. Sensitivity analysis

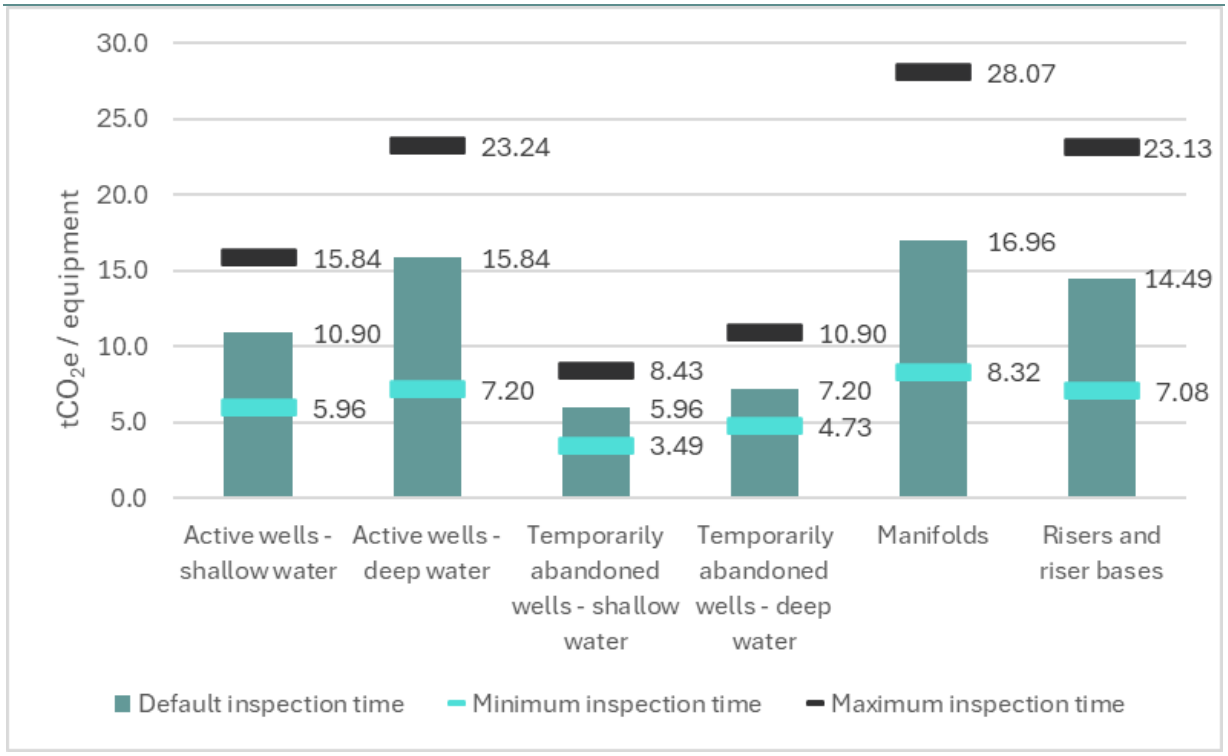
This appendix details the sensitivity of the results to each parameter. When relevant, the combined effect of several parameters is highlighted.

C.1 Equipment inspection

Sensitivity to the inspection time

Figure 19 shows the carbon footprint of equipment inspection in the default scenario and if the minimum and maximum values for the inspection time are applied (all other parameters being equal). The range of values per equipment type is the one displayed in Table 6.

Figure 19 - Sensitivity of the carbon footprint of equipment inspection to the inspection time



Source: Carbon Limits analysis, 2024

As shown in Section 4.1, emissions due to fuel combustion during the inspection represent the main share of the carbon footprint. Therefore, the results are highly sensitive to the inspection time. Based on the minimum and maximum values communicated by service providers, the carbon footprint of well inspection can be 55% lower and 51% than in the default scenario. Similarly, the results for manifolds and risers can be -51% / +66% when compared to the default value.

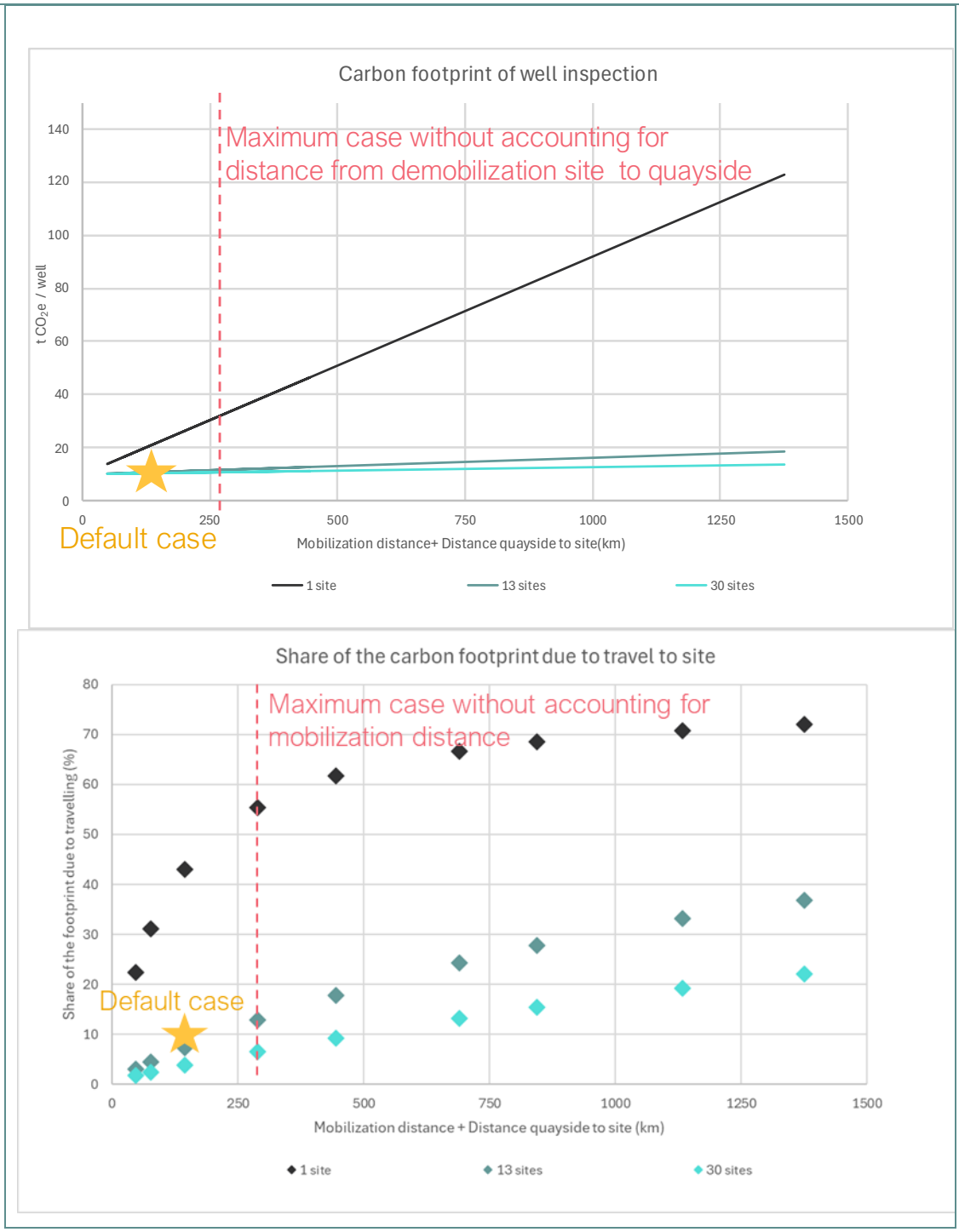
Sensitivity to the traveling distances

As can be expected, the more sites inspected in a single vessel mobilization, the lower the emissions per well are, and the smaller the share of footprint due to travelling, as the carbon footprint will be shared among a larger sample size. Similarly, the farther the distance traveled, the higher the emissions and the higher the share of the footprint due to travelling will be.

At the default travel distance (145 km), mobilizing the vessel for a unique site inspection instead of 13 sites doubles the carbon footprint. When only one site is inspected, direct emissions due to travel represent 43% of the total carbon footprint of well inspection. If the distance from demobilization site to quayside is accounted for, then the carbon footprint of inspection (assuming maximum distance from quayside to site)

increases by 58% if 13 sites are inspected, by 28% if 30 sites are inspected and by 264% if 1 site is inspected. This analysis shows the importance of planning an inspection campaign to avoid mobilizing a vessel for a single site inspection. That is particularly important for fields in remote locations, when vessels are not mooring in nearby ports.

Figure 20 - Sensitivity of the carbon footprint of well inspection (active well – shallow water) as a function of travel distances and the number of inspected sites in a single mobilization

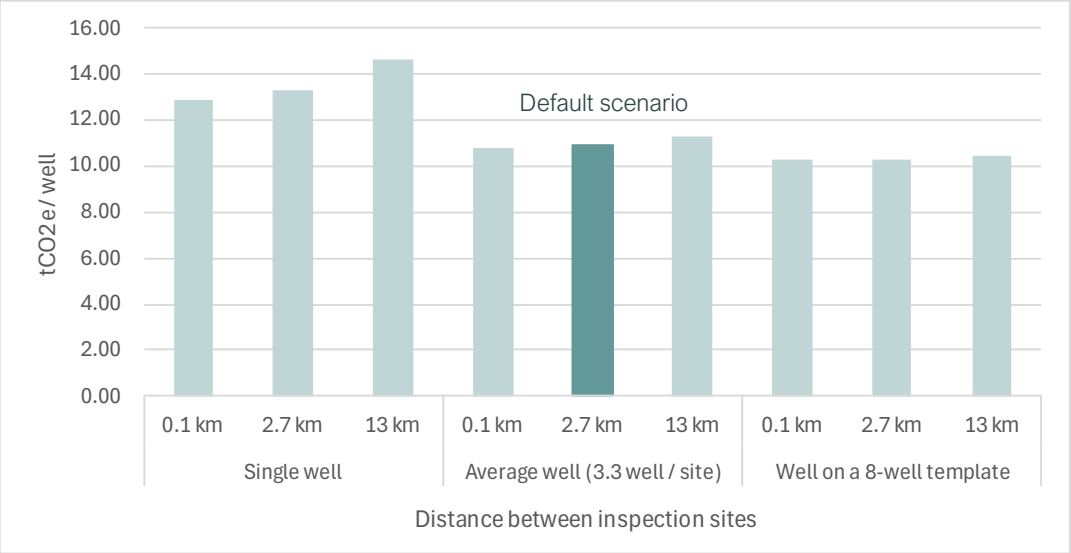


Source: Carbon Limits analysis, 2024

Sensitivity to the distance between sites

Figure 21 presents the variation in carbon footprint of well inspection depending on the number of wells per site and the average distance between sites. The default assumption is that, on average, 3.3 wells are surveyed, with a distance of 2.7 km between them, which results in a carbon footprint of 10.9 tCO_2e / well.

Figure 21 – Carbon footprint of well inspection (active well – shallow water) depending on spatial distributions of sites and wells.



Source: Carbon Limits analysis, 2024

The more wells per site, the less the effect of the travel distance because the impact of traveling is shared on a large sample of equipment. In the least favorable case (1 well per site and 13 km between sites), the carbon footprint increases by 3.8 tCO_2e / well compared to the default.

Considering the range of values for the distance between sites (0.1 to 13 km distance between sites), the spatial distribution of the sites inspected during a same mobilization has a low importance relative to other parameters.

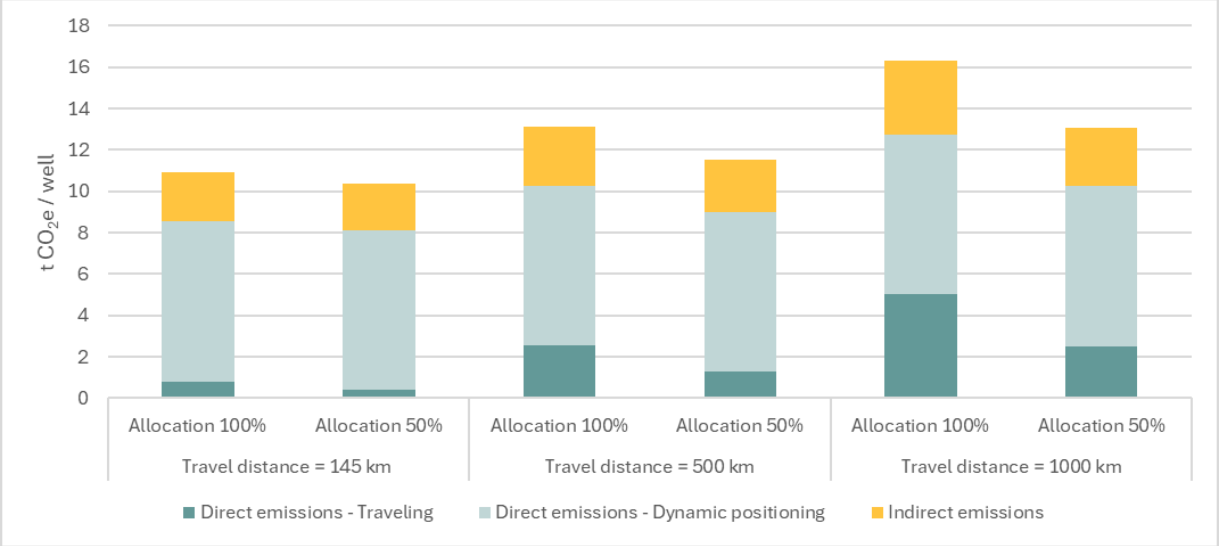
Sensitivity to the allocation of the vessels to inspection

Often, vessel operations may not be exclusive to performing leak inspections, quantifications or repairs. Operators may try and use time and resources efficiently by "grouping" different activities within a single vessel deployment. Therefore, if other activities are carried out during the same vessel mobilization, part of the impact of traveling should be allocated to other activities, thus decreasing the carbon footprint of the inspection. The sensitivity of the carbon footprint of an inspection to the allocation of emissions associated with the activity as well other activities was examined, with results presented in Figure 22.

By default, the allocation of the vessel to performing the inspection is 100% (therefore assuming the sole purpose of the deployment is for the inspection). Figure 22 compares the results when assuming an allocation of 50% (*i.e.*, on average, 50% of the time and resources of the vessel mobilization are allocated to other activities) at various travel distances: 145 km, 500 km and 1000 km.

At a minimum assumed travel distance of 145 km, the carbon footprint of the 50% allocation is decreased by 4% compared to 100% allocation, thus resulting in very little overall impact on the allocation assumption. At the maximum travel distance, the carbon footprint of the 50% allocation decreases by 21% compared to a 100% allocation. Therefore, the sensitivity of the carbon footprint to the allocation increases with increasing travel distances, and the choice of allocation becomes more significant as the travel distance increases.

Figure 22 - Sensitivity of the well inspection depending on the allocation of vessel operations



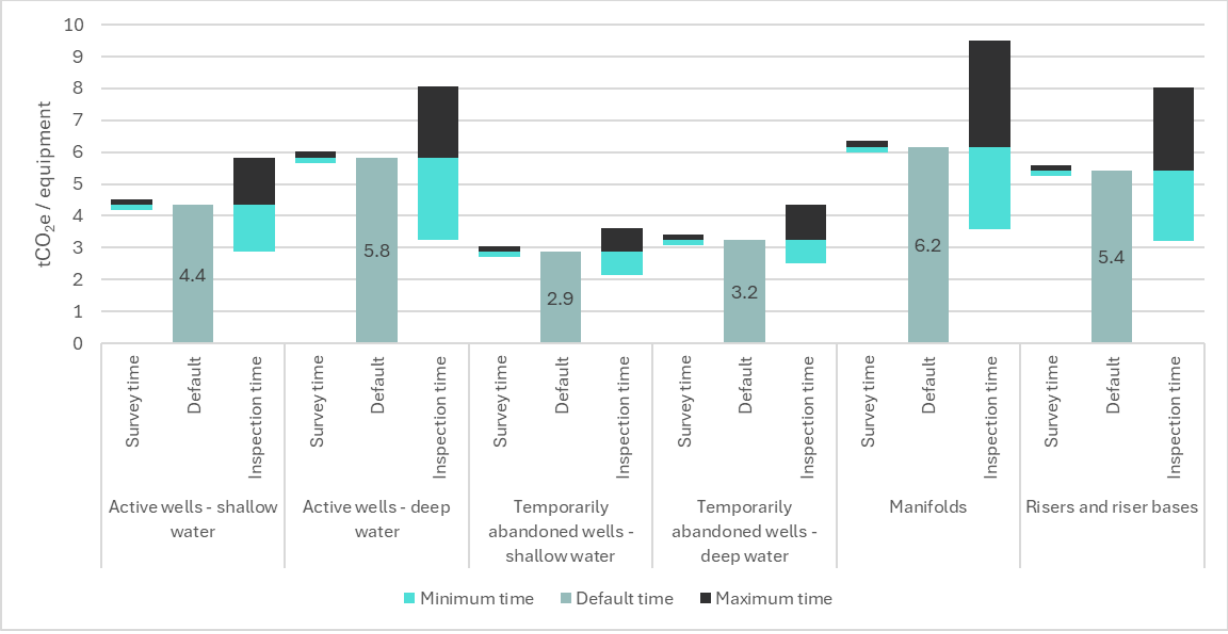
Source: Carbon Limits analysis, 2024

C.2 Equipment survey

Sensitivity to survey time

As shown in Section 4.2, the carbon footprint of equipment depends on the time needed to survey each equipment and, on the time needed to inspect the equipment as a follow-up if emissions are detected during the survey. Figure 23 shows the carbon footprint of equipment survey in the default scenario, the range of results for different survey times (left-hand side of the default bars), and the range of results for different inspection times (right-hand side of the default bars).

Figure 23 – Carbon footprint of equipment survey depending on survey time and inspection time



Source: Carbon Limits analysis, 2024

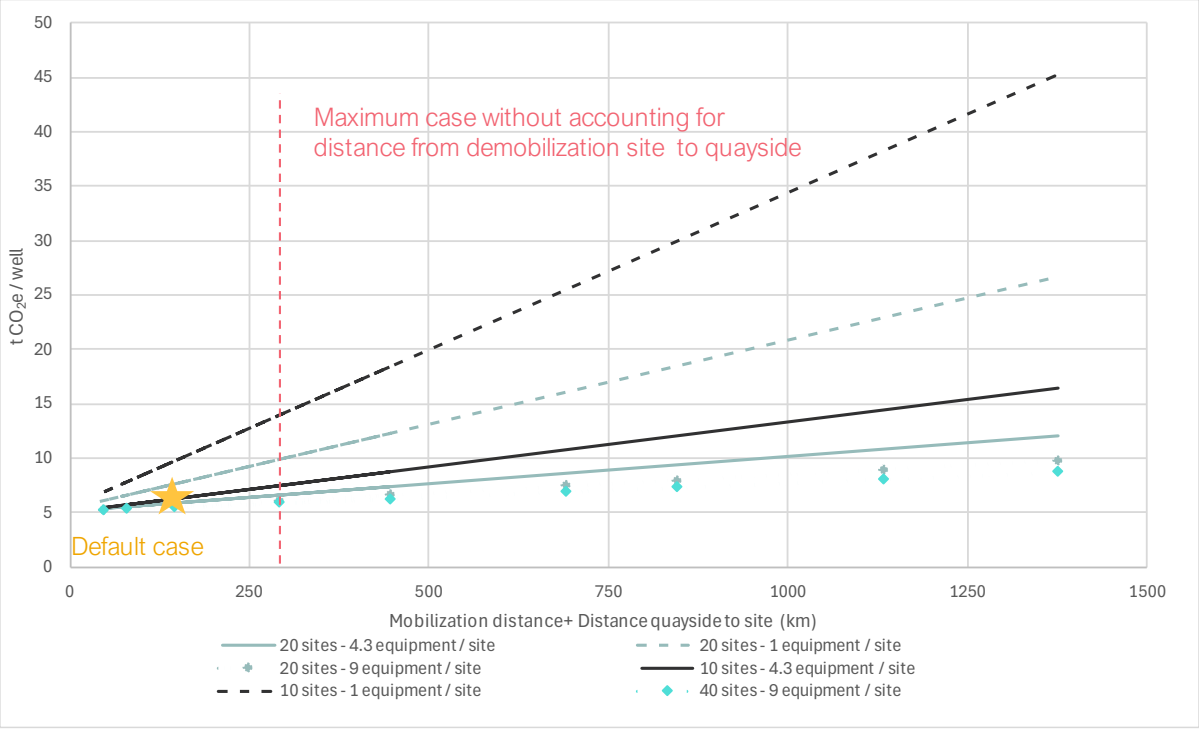
For all equipment, the inspection time is longer than survey time. Moreover, the ranges given by service providers are narrower for survey time (0.15 to 0.29 h / equipment) than for inspection time (2 to 6 h / well for example for active wells in shallow water). Consequently, the results are not very sensitive to survey time.

Sensitivity to spatial distribution

Figure 24 shows the carbon footprint of well survey depending on the distance travelled under different conditions of number of equipment and sites. Similarly to equipment inspection, for the MBES survey, the more sites surveyed, the lower the emissions per well. The farther the distance, the higher the emissions and the higher the share of the footprint due to travelling.

When the distance gets longer, the total number of equipment pieces inspected impacts more the results. The total number of equipment is the product of the number of sites by the count of equipment per site. Both the number of sites surveyed and the number of pieces of equipment per site are parameters assessed with a low level of confidence.

Figure 24 - Carbon footprint of well survey (active well – shallow water) depending on travel distance and number of elements surveyed.



Source: Carbon Limits analysis, 2024

At the default traveling distance, surveying 1 piece of equipment per site instead of 4.3 increases the footprint by 30%. If in addition, only 10 sites are surveyed instead of 20, the footprint increases by 34% more. Therefore, survey of isolated elements leads to higher carbon footprint by elements.

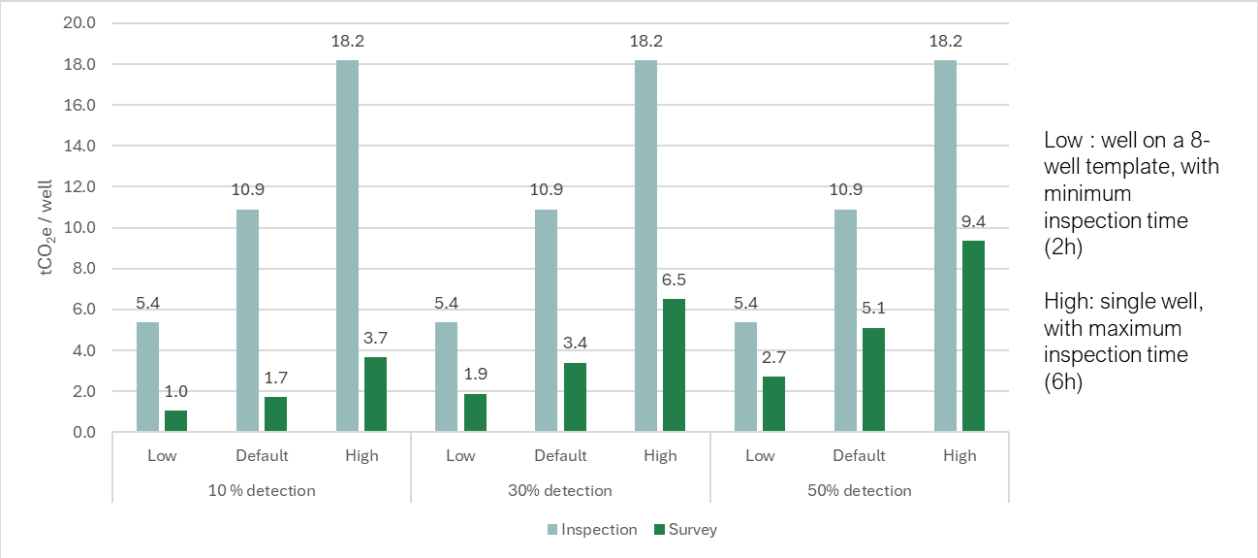
Similarly to equipment inspection, the distance from demobilization site to quayside is not included in the default scenario. However, accounting for that distance can lead to increasing the carbon footprint by up to 83% for wells at 290 km from quayside.

Equipment survey – Sensitivity to detection rate

The share of detection characterizes how many confirmation inspections in average are needed as a follow up to the survey. The higher the share of detection, the higher number of inspections must be carried out and thus the larger the carbon footprint. This parameter acts jointly with the different parameters influencing the carbon footprint of 1 inspection: the larger the carbon footprint of the inspection, the larger the carbon

footprint of the survey as well. Figure 25 illustrates this principle by putting side to side the carbon footprint of well inspection and well survey in 3 inspection scenarios: the default scenario, the low scenario (maximum number of wells and minimum inspection time) and the high scenario (minimum number of wells and maximum inspection time).

Figure 25 – Comparison of the carbon footprint of well inspection and well survey depending on the share of detection during the survey (active well – shallow water)



Source: Carbon Limits analysis, 2024

For example, increasing the share of detection from 30% to 50%:

- in the default scenario for inspection (10.9 tCO2e / well), it increases the carbon footprint of survey by 1.7 tCO2e / well (+50%)
- in the high scenario for inspection (18.2 tCO2e / well), it increases the carbon footprint of survey by 2.8 tCO2e / well (+44%)

In the cases studied, the carbon footprint of the survey with follow-up inspection is always lower than the footprint of regular inspection. However, the larger the share of detection, the smaller the difference.

C.3 Leak quantification

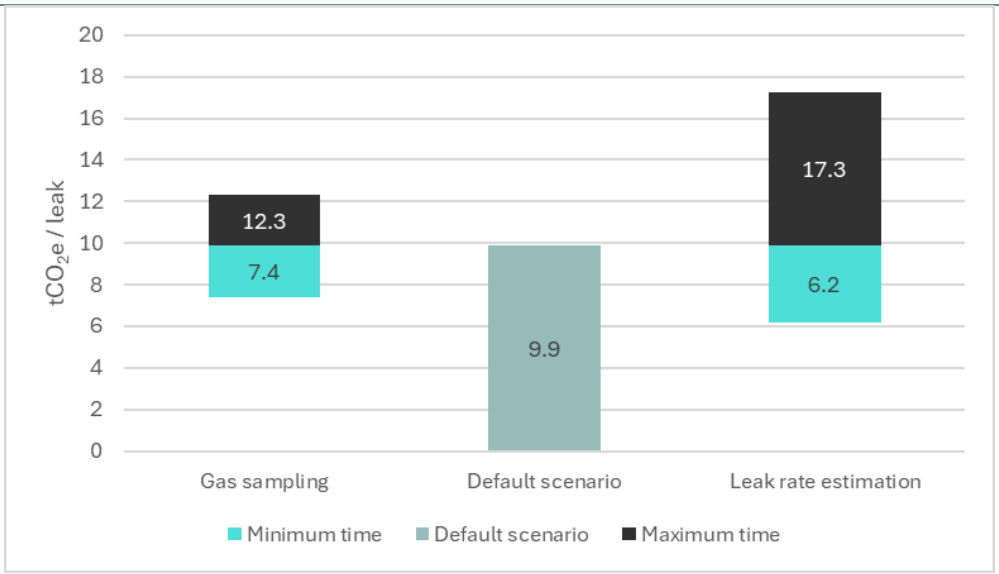
Sensitivity to leak quantification parameters

Figure 26 presents the sensitivity of the carbon footprint to performing leak quantification based on the range of time to perform activities.

The default scenario results in emissions of 9.9 tCO_2e / leak. The dynamic positioning to hold the vessel on the spot during the activities is directly linked to the time needed for gas sampling and for leak rate estimation. By varying the gas sampling time, the carbon footprint may vary from 7.4-12.3 tCO_2,e/leak, while varying the time of the leak rate estimation, the carbon footprint may vary from 6.2-17.3 tCO_2,e/leak.

There is equal importance between the two activities, but the range given by operators and service providers is larger for leak rate estimation. Indeed, in the model, leak rate estimation is done through a bubble count which requires a stabilization of the leak surroundings to be precise. Time needed for leak rate estimation is therefore dependent on ambient conditions.

Figure 26 - Sensitivity of the leak quantification to varying sampling and rate estimation times



Source: Carbon Limits analysis, 2024

C.4 Leak repair

Sensitivity to repair time, allocation and distance

Figure 27 presents the carbon footprint of leak repair depending on the travel distance due to the repair times and travel distance.

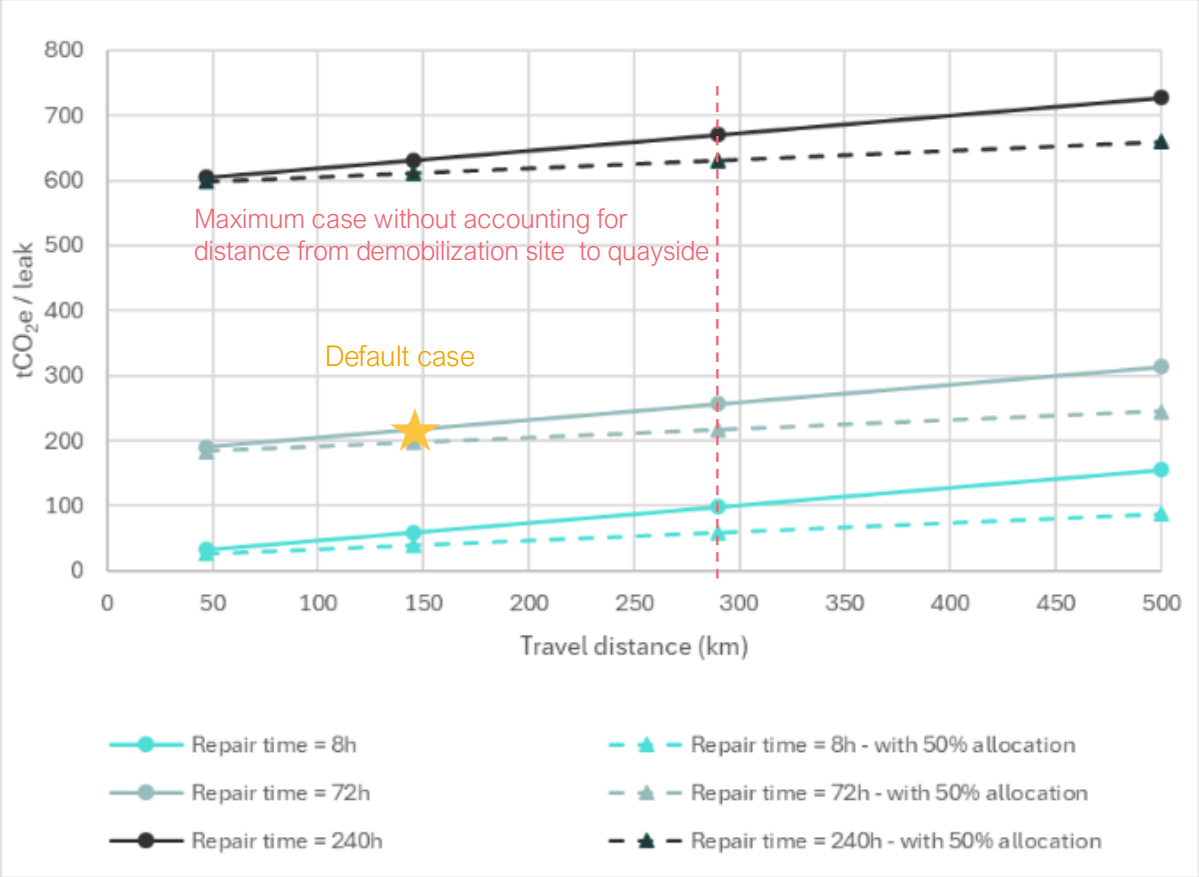
Given the high variability of possible repairs, repair times of 8, 72 and 240 hours are considered, with allocations of either 50% or 100%.

Considering the difference between travel time and repair time, repair time is the most influential parameters in the carbon footprint calculation: the carbon footprint decreases by 73% at 145 km and by 50% at 500 km with the minimum repair time compared to the default. It increases by 191% at 145 km and by 133% at 500 km with the maximum repair time compared to the default.

The travel distance also impacts greatly the results because it is assumed that the vessel mobilization is dedicated to a unique repair. The difference between the minimum and the maximum distance from quayside to site results in a difference of 66 tCO_2e / leak.

Performing repairs in addition to other activities (50% allocation) can reduce the footprint by 9 to 43% at 500 km, for maximum and minimum repair times respectively. Other activities encompass inspection, cleaning and maintenance or even a second repair on another piece of equipment.

Figure 27 - Sensitivity of the carbon footprint of leak repair on distance travelled and repair time



Source: Carbon Limits analysis, 2024

CARBON LIMITS

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Carbon Limits AS
@CarbonLimitsAS

Stensberggata 27
0170 Oslo
Norge

+47 988 457 930
www.carbonlimits.no

