GHG impact assessment of vertical/cross-domains use cases based on revised ITU-T L.1480 recommendation

Release 1.0

AIOTI WG Green ICT Enablement

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Executive Summary

This Report builds on the previous AIOTI report IoT and Edge Computing Carbon Footprint Measurement Methodology R3.

The main objective of this deliverable is to provide examples of use cases that can be assessed based on their GHG emissions, assuming that ICT is used as a Green enabling technology. The objectives of this report are:

- briefly introduce the standardised GHG assessment methodology specified in the revised ITU-T L.1480 recommendation;
- overview of Green ICT enabled vertical/cross-domains use cases;
- provide examples on GHG impact assessment of vertical/cross-domains use cases based on revised ITU-T L.1480 recommendation.

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1. Introduction

The main objective of this Report is to provide examples of use cases that can be assessed based on their GHG emissions assuming that ICT is used as a Green enabling technology. The objectives of this report are:

- briefly introduce the standardised GHG assessment methodology specified in the revised ITU-T L.1480 recommendation;
- overview of the following Green ICT enabled vertical/cross-domains use cases:
  - Vertical use cases:
    - “Smart Monitoring System in Windfarms”;
    - “Visual inspection for automated Product Quality assessment”;
    - “Edge-cloud based visual inspection for automated Product Quality assessment”.
  - cross-domains use case:
    - Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)”;
- provide examples on GHG impact assessment of the following vertical/cross-domains use cases based on revised ITU-T L.1480 recommendation:
  - Vertical use cases:
    - GHG impact assessment of “Smart Monitoring System in Windfarms” use case;
    - GHG impact assessment of “Visual inspection for automated Product Quality assessment” use case;
    - GHG impact assessment of “Edge-cloud based visual inspection for automated Product Quality assessment” use case;
  - cross-domains use case:
    - GHG impact assessment of Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)” use case;
      - The GHG emissions assessment process and results described for this cross-domain use case are preliminary and are partially aligned with the revised ITU-T L.1480 methodology. It is expected that the next version(s) of this report will include an accurate assessment alignment with the revised ITU-T L.1480 methodology.

2. Overview of Revised ITU-T L.1480 Recommendation

The revised ITU-T L.1480 (07/25) recommendation provides a methodology for assessing how the use of information and communication technology (ICT) solutions impacts greenhouse gas (GHG) emissions of other sectors.

The revised ITU-T L.1480 (07/25) recommendation updates the ITU-T L.1480 (12/22) recommendation by two key additions:

- representation by a formula of the calculation steps, see Section 11.3.7 (this ITU-T/ETSI contribution was done by a cooperation between AIOTI, Fraunhofer IIS, Orange and Huawei);
- includes two use case examples of the application of the steps in the evaluation methodology described in revised ITU-T L.1480 (07/25) recommendation:
    - case study of accelerating teleworking through the use of a remote collaborative working solution (this ITU-T/ETSI contribution was done by Orange)
    - ex-ante case study of a project of implementing monitoring of bolts for windfarms (this ITU-T/ETSI contribution was done by the cooperation between AIOTI, Fraunhofer IIS, Orange and Huawei)

This methodology provides key guidance steps on the assessment of the use of ICT solutions covering the effect of using ICT solutions on other sectors consisting of net second order effects and higher order effects such as rebound.

The key guidance steps support the assessment the net second order effect and higher order effects of the following cases:

- ICT solutions that are implemented at different scales, including at an organizational level, at a city level, at a country level or at worldwide level.
- ICT solutions seen from the perspective of users
- ICT solutions seen from the perspective of an ICT organization contributing to the ICT solutions. This includes:
    - Assessment of the effect of one or more specific ICT solutions implemented in an actual context for a specific customer.
    - Assessment of the aggregated effect of all ICT solutions provided by an ICT organization across some or all its customers

This methodology covers different depths of assessment, referred to as Tier 1–3. A short description of these assessment depths is provided below (copied from revised ITU-T L.1480 (07/25) recommendation):

- **Tier 1 assessments**: Tier 1 assessments shall assess net second order effects and shall also assess impact from contextual factors and higher order effects, by quantitative means if such assessment is considered robust, or else by qualitative means. These assessments are the most in-depth ones.
- **Tier 2 assessments**: Tier 2 assessments shall assess net second order effects and shall identify contextual factors and higher order effects. These are assessments of intermediate depth which do not assess the magnitude of higher order effects.

- **Tier 3 assessments**: Tier 3 assessments shall consider net second order effects and should identify contextual factors and higher order effects. These are the simplest assessments and are not considered rigorous.

Moreover, this methodology covers the assessment of the following environmental effects (copied from revised ITU-T L.1480 (07/25) recommendation):

- **first order effect**: Direct environmental effect associated with the physical existence of an ICT solution, i.e., the raw materials acquisition, production, use and end-of-life treatment stages, and generic processes supporting those including the use of energy and transportation.

- **second order effect**: The indirect impact created by the use and application of ICTs which includes changes of environmental load due to the use of ICTs that could be positive or negative.

- **higher order effect**: The indirect effect (including but not limited to rebound effects) other than first and second order effects occurring through changes in consumption patterns, lifestyles and value systems.

Each of the depths of assessment is associated with specific requirements on data quality and provides specific guidance for the consideration of rebound effects. Moreover, the revised ITU-T L.1480 (07/25) recommendation addresses assessments from three different time perspectives:

- Ex-ante, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution(s);

- Mid-way, i.e., an assessment of a present situation during the operational life of the ICT solution(s);

- Ex-post, i.e., a retrospective assessment that takes place after the assessed operation period of the ICT solution(s).

The current version of the revised ITU-T L.1480 (07/25) recommendation is limited to assessment of GHG emissions. However, in principle, it could also be used to identify other environmental effects such as the impacts identified in ITU-T L.1410.

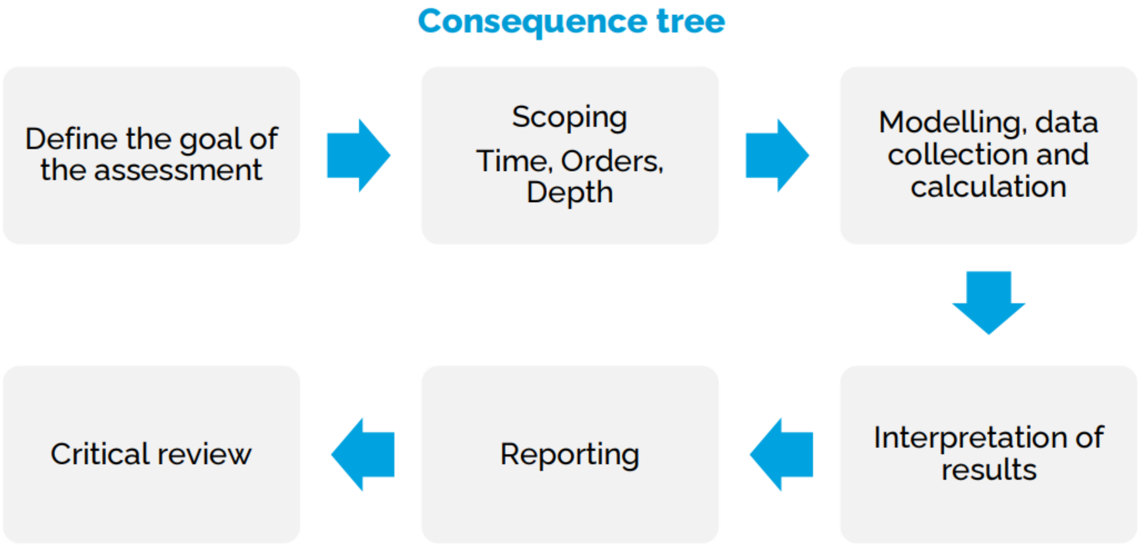


Figure 1: Six steps to assess the impact of the use of an ICT solution, copied from Jean-Manuel Canet presentation at ITU ETSI Symposium, December 11-12, 2024

The key guidelines steps are depicted in Figure 1 and briefly described below (for more details please see revised ITU-T L.1480 (07/25) recommendation:

Step 1 – Define the goal of the assessment

1.1) Define the aim and type of the assessment

1.2) Define the assessment depth: Tier 1, Tier 2 or Tier 3

Step 2 – Scoping

2.1) Define the scope by:

- Defining the ICT solution(s) and their main second order effects
- Defining the functional unit
- Defining the assessment perspective
- Defining the composition of the ICT solution(s) and identifying the contributors to its overall first order effects
- Identifying and defining the reference scenario(s)
- Identifying additional second and higher order effects of the ICT solution(s) and any relevant contextual factors and document those together with main second order effect and the first order effects following the guidelines for establishment of a consequence tree; A consequence tree is very important in the assessment process and provides an analytical basis for identifying the effects induced as consequence of the deployment and use of the ICT solution, and delivers a set of collateral effects (consequences) connected to the solution in addition to its main second order effect.
- Selection of effects to be quantified
- Defining the system boundaries of the ICT solution(s) and the reference scenario(s)

Step 3 – Modelling, data collection and calculation

3.1) Quantify the second order effect of each assessed ICT solution through:

- Identifying the overall usages of the ICT solution while separating modifying and rebound usages
- Quantifying the aggregated first order effect of the ICT solution(s)
- Quantifying the change of GHG emissions due to changes in the reference activities
- Deriving the net effect of the ICT solution(s) in a standalone scenario

3.2) Quantify the combined induced effect of several ICT solutions addressing the same emissions

3.3) Assessment of higher order effects including quantification

Step 4 – Interpretation of results

Perform interpretation of results through:

4.1) Evaluation of the applied method

4.2) Data quality analysis

4.3) Sensitivity analysis

4.4) Uncertainty analysis

Step 5 – Reporting

5.1) Perform reporting according to the guidance

Step 6 – Critical review

6.1) Perform critical review according to the guidance

3. Vertical/cross-domains use cases

This section provides the descriptions of the vertical and cross-domains use cases that will be GHG assessed, using the revised ITU-T L.1480 (07/25) recommendation as shown in Section 2.

3.1 Vertical use cases

3.1.1 Monitoring System in Windfarms

This section provides an overview of the use case: "Smart Monitoring System in Windfarms".

3.1.1.1 Description

Motivation: The aim of this use case is to apply a smart monitoring system, i.e., the use of this remote bolt monitoring solution to reduce GHG emissions for its user, i.e. the company operating an onshore or offshore wind farm.

Vertical Sector/domain: This use case is applied in the Energy and Building/City vertical sectors.

Evaluation Type of ICT Solution: The type of evaluation is a specific ICT solution implemented in a specific context (i.e. a demonstrator presented as a pilot system). No commercially deployed Smart Monitoring System in Windfarms is available;

Assessment Time:

- Ex-ante, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution(s);

3.1.1.2 Source

Monitoring of bolted joints – wireless, self-powered and retrofittable

(Later to add reference to rev. ITU-T L.1480)

3.1.1.3 Roles and Actors

- Potential users of the pilot solution (windfarms), currently, there were no identified users from whom to evaluate the actual effects of the use of the solution (in the context of helping the GHG emission assessment)

- Potential experts are identified to provide interviews on the maintenance activities in onshore and offshore wind farms (in the context of helping the GHG emission assessment)

- Potential suppliers for industrialising ICT solution, to develop products and offer; They can provide interviews (in the context of helping the GHG emission assessment)

3.1.1.4 High level operation

High-level operations of the reference scenario

The use case is focused on the onsite maintenance of bolts on wind turbine/windfarms. This maintenance requires the turbine to be shut down (no or less power feed into the grid); see Figure 2.

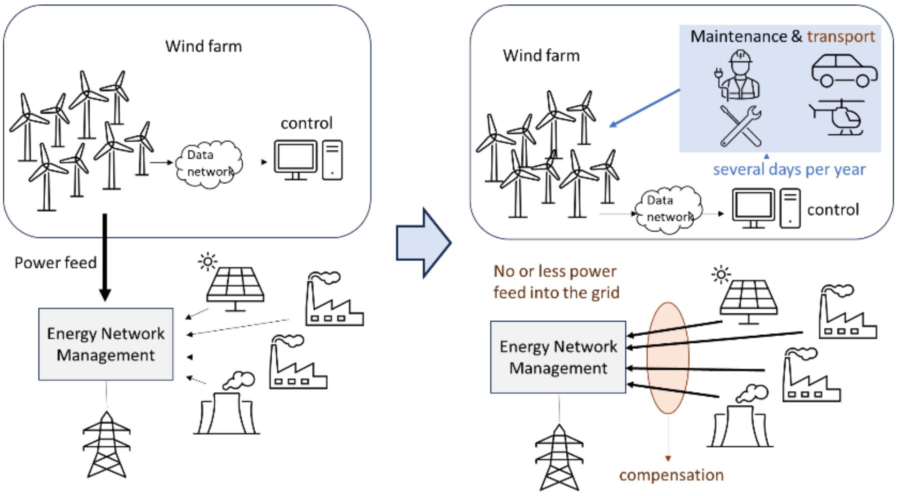


Figure 2: Windfarm in operating mode/Wind farm in maintenance & inspection mode

High-level operations of the Green ICT enabled scenario

As this maintenance requires the turbine to be shut down Figure 2, a reduction in this downtime could increase the turbine's availability to produce energy.

In particular, this would improve the wind turbine's load factor (equal to the ratio between actual electricity production and the theoretical (i.e. nominal) maximum production over a given period): the aim is to increase the turbine's availability rate.

The decrease in GHG emissions generated by changes in maintenance operations would then result from Figure 3:

- the replacement of wind energy not produced during maintenance operations by energy from mixed sources available in the country where the wind turbine is located, and
- the reduction in transport to the wind farm site for maintenance and related operations.

This bolt monitoring solution could also help prevent failures in wind turbines.

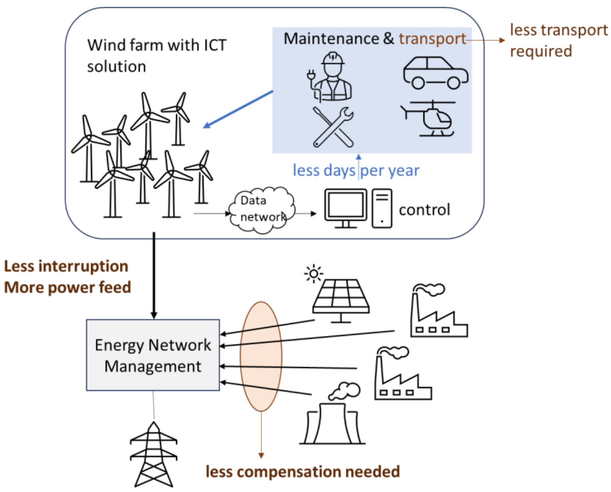


Figure 3: Main expected GHG emissions effect of use of bolt monitoring ICT solution (Smart Monitoring System)

3.1.1.5 Willingness to work on assessment

Specify whether you would like to work together with GIE WG colleagues on collecting necessary data to complete the GHG assessment of your use case based on the revised ITU-T L.1480 specification:

- Yes

3.1.2 Edge-cloud based visual inspection for automated Product Quality assessment

This section provides an overview of the use case: "Edge-cloud based visual inspection for automated Product Quality assessment".

3.1.2.1 Description

Motivation:

The main aim is to promote an AI-powered automated industrial visual inspection system for quality assurance in manufacturing processes that can increase energy and operational efficiency, and reduce GHG emissions. The deployment of this advanced fiber-based ICT solution can contribute to:

  - Aligning with the Net Zero initiative.
  - Focusing on key stages related to emissions.
  - Reducing GHG emissions and improving energy efficiency.
  - Promoting Sustainability by supporting autonomous networking for secure and efficient industrial processes.
- What are the business drivers, which are the values for the stakeholder types (e.g., several stakeholder types will participate and profit from this use case, and at the same time reduce GHG emissions)

Business drivers:

  - An automated AI-based visual inspection system for quality assurance decreases human error while providing consistent, high-quality defect detection.
  - Identifying defects early minimizes material waste and emissions incurred during reprocessing and is therefore beneficial for GHG reduction.
  - This system can also automate repetitive, manual tasks within inspection processes, enabling higher inspection throughput and scalability while reducing the labor costs.
  - The automation of visual inspection also increases the number of inspected manufactured artefacts per hour, leading to higher productivity and larger output volumes.
  - Using automation reduces the size of QA teams, overtime levels, and the manual system.
  - Reducing defective units and minimizing excess runs during production lowers overall energy and material use. This provides tangible GHG emissions reduction from decreased waste, energy use, and defective products.
  - Improves product reliability and quality, with lower returns and increases customer satisfaction.
  - This system supports data-based decisions, predictive maintenance, and industrial digitalization.

- **Vertical Sector/domain**
    - The application of the study results (e.g., internal improvement, public disclosure, certification) is to be specified and needs to mention whether the results are intended to be used in comparative assertions intended to be disclosed to the public.
    - The use case will be applied in manufacturing industries. At this stage, the results are not intended to be used for comparative assertions disclosed to the general public. However, future dissemination or public communication can be considered depending on the objectives and requirements of the participating stakeholders.
- **Evaluation Type of the ICT Solution**
    - The type of evaluation is a specific ICT solution implemented in a specific context (i.e. a demonstrator presented as a pilot system). Commercial deployment is not taken into consideration.
- **Assessment Time/Type:**
    - Ex-ante, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution

3.1.2.2 Source

AIOTI Computing Continuum Report (Section 9, pages 49-55)

3.1.2.3 Roles and Actors

- Suppliers for industrializing the ICT solution. These suppliers are involved with developing the products and services and can be interviewed if needed to support the GHG emission assessment efforts.
- Supplier of robot.
- Potential users of the pilot solution, which are manufacturing industries.

Fraunhofer HHI is in contact with the manufacturers of the ICT solution and the robotic arm for data collection. If the final decision from the manufacturers is not to share the data, then other vendors will be contacted.
Regarding the use phase of the PON-based ICT solution, Fraunhofer HHI will provide primary data.

3.1.2.4 High level operation

3.1.2.4.1 High-level operations of the reference scenario

This scenario presents traditional quality assurance processes (Figure 4) in a manufacturing environment. It is less efficient and resource-intensive than the advanced fiber-based and edge cloud solutions. The reference scenario would include:

Human-Based Inspection:

Quality assurance is performed by human workers who visually inspect products on the production line and the number of required workers depends on the conveyor belt size and the intensity of incoming parts. This process is labor-intensive, time-consuming, and prone to human error, leading to inconsistencies in quality control. Human-based inspection may lead to higher demand for physical infrastructure, increasing the carbon footprint from maintaining multiple inspection stations.

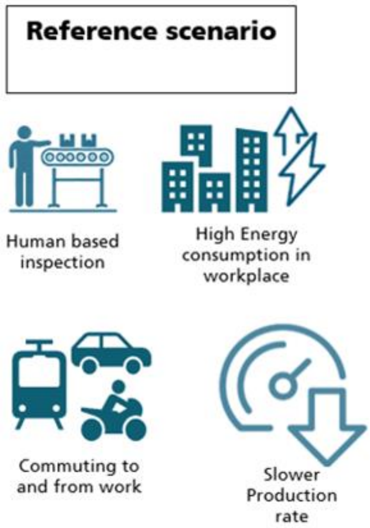


Figure 4: Visual presentation of reference scenario

Higher transportation usage

For human inspection, there is an increase in the commuting of human workers to the workplace.

High Energy Use

The on-premises hardware without centralised computing has higher energy usage. The lack of centralised optimisation results in inefficient energy usage. The energy usage of human labour also adds up to the overall energy usage at the workplace.

Slower Production Process

Traditional inspection processes are slower and less accurate. Defects may go unnoticed, and this may result in higher scrap rates and rework costs.

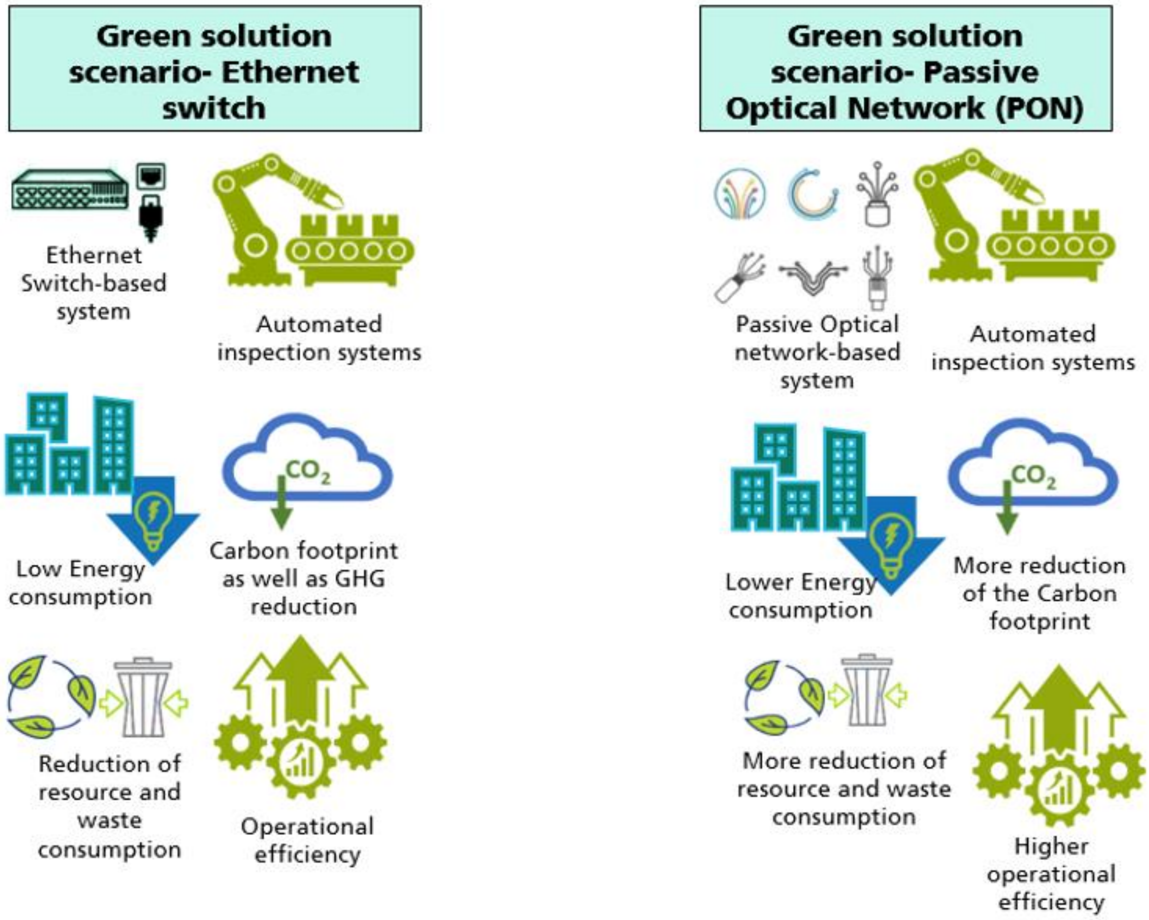
The reference/ baseline scenario in the visual inspection use case represents a traditional, inefficient, and resource-intensive approach to quality assurance. By transitioning to fiber-optics and edge cloud-based solutions, manufacturers can achieve significant improvements in efficiency, scalability, and sustainability, while also addressing workforce and environmental challenges.

3.1.2.4.2 High-level operations of the Green ICT enabled scenario

Both Ethernet switch-based and PON- based ICT solution are considered to define the Green ICT-enabled scenario and to compare with the reference scenario. The main effect of the Green ICT-enabled scenario is to replace the Traditional human inspection-based Quality Assurance process by introducing an edge cloud computing-based automated Quality Assurance system, which can improve the industrial production processes ((a) (b)

Figure 5). The system uses high-definition industrial cameras to capture pictures of the products on a conveyor belt, uses artificial intelligence (AI) to assess them for flaws and manufacturing defects. This edge cloud-based visual inspection system optimizes energy use by reducing on-site computational resources. This shift also reduces physical infrastructure needs, lowering emissions from transportation and on-site operations.

Here, both Ethernet switch and PON solutions are significant steps forward compared to the human-based reference scenario, particularly in reducing energy use, lowering carbon emissions, and enabling higher efficiency.



(a) (b)

Figure 5: ICT solution scenarios (Ethernet switch based (a) vs PON based (b)); main GHG emission reduction related effect for the introduction of ICT solution

Here, the first improvement pathway is the Ethernet switch-based solution where, human inspection is replaced by automated inspection systems supported by electric and Ethernet switches, thus moving us away from manual, commute-dependent labor. This already brings clear benefits a low energy consumption, a reduction in carbon footprint and greenhouse gases, less resource and waste consumption, and greater operational efficiency compared to the reference scenario.

The second improvement pathway which is the PON-based solution goes further. By shifting to fiber-optic networks, more gains can be achieved. It integrates fiber-to-the-camera and fiber-to-the-robot via a Passive Optical Network (PON) system consisting of an Optical Line Terminal (OLT) and Optical Network Units (ONUs). The Visual Inspection Station (VIS) interfaces with the edge/cloud using ONUs. Each ONU supports one camera or a robotic arm within the VIS. The demonstration establishes an end-to-end control loop comprising a camera (observation) → the edge/cloud (analysis) → robotic arm (action). The end-to-end observe-analyse-act (OAA) procedure provides an end-to-end video processing pipeline with remote computational capabilities.

Replacing traditional electric switches-based systems with optical network systems enhances energy efficiency due to the lower power consumption of optical components, while simultaneously improving data processing and reducing hardware dependence tasks. As a result, fiber networks enable most efficient data transmission, lowering energy use and reducing the carbon footprint of industrial operations.

In addition, the use of a robotic arm in combination with the virtual Programmable Logic Controller (vPLC) that runs on the edge cloud sorts the objects based on the feedback of AI-based defect detection, and operates using the control signals received from the edge cloud. The robotic arm is collocated with the conveyor belt. This system leads to less human intervention. The robotic arm sorts the manufactured artefacts, where faulty products are discarded and non-faulty products are put onto the conveyor belt to continue into production.

ICT solution under study

In this use case scenario, as illustrated in Figure 6, the industrial camera captures images of products on the production line. Captured images are sent to the edge-cloud for AI-based analysis. AI classifies objects as faulty or non-faulty based on predefined criteria, using pre-trained Machine Learning (ML) algorithms. The robotic control system receives sorting commands using the vPLC running on the edge cloud.

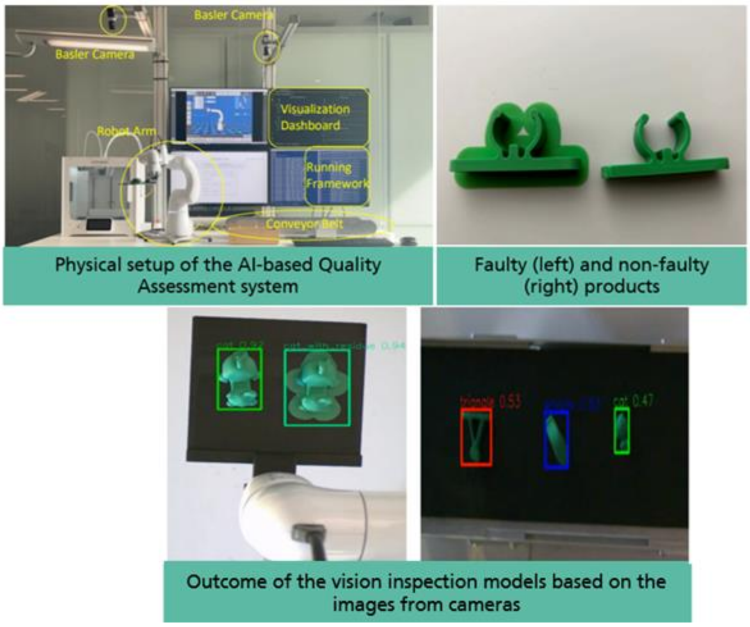


Figure 6: ICT solution use case scenario; Source: AIOTI, 2024.

Hence, this end-to-end ICT solution requires the following functions:

1. Industrial cameras that capture high-resolution video of items on a production line and ensure proper lighting and positioning for accurate fault detection.
2. Edge cloud data centre. Server responsible for performing the video analysis and processing, and for the telemetry framework and machine learning pipeline operation.
3. Application: Edge-Cloud AI Processing that analyses images of manufactured artefacts and looks for defects in real time.
4. A control System (i.e., vPLC) of the robotic arm is used to support the operation of the robot arm and the communication of the control signals received from the edge-cloud. This system runs on the third server.
5. For Ethernet based solution, Ethernet switches, core switch and access switches to ensure a smooth network communication between the operation floor and the edge-cloud.

6. For Optical based solution, PON components which interconnects all the components to ensure high-speed, low-latency communication between the operation floor and the edge-cloud.

3.1.2.5 Willingness to work on assessment

Specify whether you would like to work together with GIE WG colleagues on collecting necessary data to complete the GHG assessment of your use case based on the revised ITU-T L.1480 specification:

- Yes

3.2 Cross-domain use cases

3.2.1 Positive Energy Districts

This section contains a group of use cases that are using and focusing on the concept of Positive Energy Districts (PED). The basic principle of a PED is to create an area within the city boundaries, capable of generating more energy than is used, and agile/flexible enough to respond to energy market variations. Rather than simply achieving an annual net energy surplus, it should also support minimizing impacts on the connected centralized energy networks by offering options for increasing onsite load-matching and self-use of energy, technologies for short- and long-term energy storage, and providing energy flexibility with smart control.

In particular, PEDs can include all types of buildings present in the urban environment, and they are not isolated from the energy grid. Within the research community, the PED is an emerging concept intended to shape cities into carbon neutral communities in the near future. Reaching the goal of a PED requires firstly improving energy efficiency, secondly cascading local energy flows by making use of any surpluses, and thirdly using low-carbon energy production to cover the remaining energy use. Smart control and energy flexibility are needed to match demand with production locally as far as practical, and also to minimize the burdens and maximize the usefulness of PEDs on the grid at large.

The Implementation Working Group on Smart Cities of the Strategic Energy Technology Plan for Europe (SET Plan) was established in October 2018 with the mission to bring about 100 urban districts or neighbourhoods in Europe by 2025 with a clear commitment to sustainability, liveability and going beyond carbon neutrality by becoming energy positive. Such "Positive Energy Districts/Neighbourhoods" (PED/PENs) could be new developments but should also implement ambitious solutions for urban district renewal. About 20 European countries are currently participating in this initiative, which also involves problem owners, as well as key stakeholders from industry.

According to the white papers: "White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods" and SET-Plan 3.2 Programme on Positive Energy Districts, the following definitions were proposed:

- "Positive" refers to produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy.
- "Energy" is divided into renewable energy and non-renewable energy.
- "Districts" refer to "urban areas or groups of connected buildings".

Moreover, the EU's Solution Booklet of Positive Energy Districts gives a description of PED as "An urban area with clear boundaries, consisting of buildings of different typologies that actively manage the energy flow between them and the larger energy system to reach an annual positive non-renewable primary energy balance."

The PED Programme is a mission-oriented transnational R&I funding programme, which results from the European SET Plan and is being implemented by the JPI Urban Europe. It has the ambition to realize a holistic implementation process towards 100 Positive Energy Districts and Neighbourhoods in Europe, including technological, spatial, regulatory, financial, legal, ecological, social and economic perspectives in order to provide sustainable urban development as well as quality of life and affordability in the urban environment. As a basis for such implementation measures, a common reference framework for Positive Energy Districts and Neighbourhoods has been elaborated with the aim to anticipate the various dimensions and aspects related to the realization of PEDs.

3.2.1.1 Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)

3.2.1.1.1 Description

Decentralised renewable backup and KILE[1]-related considerations:

"The economic regulation gives the grid companies an incentive to keep costs low. However, we do not want this to come at the expense of delivery reliability. The purpose of the KILE scheme is to give the grid companies an incentive to build and operate the grid with economically optimal delivery reliability. The KILE element represents the customers' costs of interruptions, and the scheme means that the customers' interruption costs are included in the grid companies' business economic assessments. The incentives in the KILE scheme are given in the form of a reduction in income, so that the grid companies' profits are reduced when an interruption occurs. How is KILE calculated? Every time an interruption occurs in the power supply, a KILE amount is calculated that represents the inconvenience to grid customers due to the interruption. KILE is calculated based on individual cost functions for each customer group. The cost functions are based on the different customer groups' willingness to pay to avoid interruptions. The functions take into account the duration of the interruption, the time of the interruption (month, day of the week, time) and whether the interruption was notified in advance or not."

In the Nordic regions such as Lofoten and Nord-Salten where high-voltage grid installations are already operational, the charging of backup systems can in itself contribute to additional grid stress and potential power interruptions of the grids. This underlines the necessity for strategically positioned alternative energy sources, particularly in emergency preparedness zones where current solutions rely heavily on diesel-based electrical generation systems. These fossil-based generators are logistically burdensome and limited in scalability, underscoring the urgency for more resilient, renewable-based alternatives.

Recent work, including preliminary assessments of small-scale wind turbines, suggests that locally installed micro-wind systems could play a vital role—not only in off-grid backup scenarios but also in feeding surplus capacity into the main grid during normal operation. This aligns with broader goals of increasing delivery quality in vulnerable parts of the network, as discussed in Statnett's FASIT system and *KILE*-based evaluations.

The logic behind this approach is twofold. First, distributed renewable assets improve preparedness by reducing dependency on centralized and fossil-based reserves. Second, such micro-installations—particularly those designed to be minimally invasive and suitable for private ownership (e.g. vertical-axis turbines or pole-mounted micro-turbines)—offer scalable models that complement the overarching objective of reducing outage-related costs (KILE penalties) by stabilizing local energy availability.

[1] https://www.nve.no/reguleringsmyndigheten/regulering/nettvirksomhet/oekonomisk-regulering-av-nettselskap/kile-kvalitetsjusterte-inntektsrammer-ved-ikke-levert-energi/

Instead of large infrastructure that risks environmental disruption, smaller, modular solutions can empower communities to maintain critical services and reduce vulnerability in the face of grid interruptions.

Motivation:

The aim is to apply a smart monitoring and actions system for unforeseen energy supplies in rural grids, by using the combination of a mix of renewable sources and battery cells recharged by using renewables, while reducing/avoiding GHG emissions from the use of fossil fuel energy supplies, such as diesel electric generators

The aim is to implement a smart system for monitoring and managing unforeseen energy needs in rural grids, while reducing greenhouse gas emissions from backup power sources. This involves replacing or supplementing conventional diesel-based standby systems with renewable alternatives such as micro-wind turbines, small-scale solar units, and modular battery storage. These sources are not only less carbon-intensive but also better suited to decentralized deployment in sparsely populated areas.

By integrating real-time monitoring with predictive analytics, the system can anticipate local energy shortages, dynamically allocate surplus from nearby microgrids, and trigger demand-side responses when necessary. This enables both a reduction in peak demand and more efficient use of locally available energy.

Additionally, by mapping outage-prone zones and consumption patterns, the solution supports more granular and climate-aware energy planning. The resulting infrastructure not only improves delivery quality but contributes directly to KILE-related cost reductions by mitigating the economic consequences of power outages. The long-term ambition is to establish a replicable model for distributed energy resilience that enhances preparedness, cuts emissions, and promotes smart electrification across vulnerable grid segments.

Business drivers

The primary business drivers for this use case are rooted in the convergence of regulatory pressure, decarbonisation targets, cost-efficiency imperatives, and grid resilience requirements.

For Distribution System Operators (DSOs) and energy utilities, the solution offers measurable value through reduced outage-related penalties (KILE), increased grid flexibility, and deferred capital expenditures on centralised infrastructure reinforcement. For municipalities and regional planners, it enables more sustainable land-use strategies by integrating decentralised renewable sources into local contingency planning, aligning with national energy and climate plans (NECPs).

Equipment manufacturers and technology providers benefit from the emerging market for modular micro-energy systems, predictive monitoring tools, and interoperable control platforms—offering scalable business models through replication across rural and peri-urban areas. End-users, particularly in sparsely populated regions, gain increased energy security, lower reliance on fossil-based emergency power, and potential cost savings through demand-side incentives and local prosumer schemes.

Finally, environmental agencies and public actors realise broader system benefits by contributing to reduced GHG emissions, fulfilling regulatory compliance with EU Green Deal objectives and strengthening adaptive capacity in the face of increasing energy volatility. Across these stakeholder groups, the model catalyses a shift from reactive energy backup to proactive, decarbonised grid management—generating economic, environmental, and societal value in parallel.

Value for stakeholder types

Provide solution use cases for reducing the costs and GHG emissions by using the combination of a mix of renewable sources and battery cells, from the use of fossil fuel energy supplies, such as diesel electric generators

The key business drivers for deploying solutions that reduce the costs and emissions of alternative fuel-based energy supplies stem from a growing intersection of regulatory accountability, cost containment, environmental performance, and system reliability. Emerging smart energy solutions—particularly predictive monitoring, localised battery storage, and modular renewables—directly address both challenges.

The main business driver is the replacement of diesel generators with low-emission systems, e.g., combination of a mix of renewable sources and battery cells charged by using renewables, for short-term backup energy. This reduces fuel costs, simplifies logistics, cuts CO_2 emissions, and avoids delivery failure penalties under regulatory schemes such as KILE.

Across European contexts, Distribution System Operators (DSOs) are increasingly measured not only by their capacity to deliver energy but by the *quality* and *continuity* of that delivery. Delivery reliability—defined as the ability of the system to sustain voltage above 95% of the contractual standard—is now subject to transparent performance metrics, including short- and long-duration outages. These are directly tied to financial adjustments under quality-adjusted revenue regulation schemes such as KILE in Norway.

Reducing reliance on fossil-based, short-minute backup power (e.g. diesel generators) represents a concrete opportunity to mitigate both operational expenses and greenhouse gas (GHG) emissions:

1. DSOs should report outage duration and frequency. Failures result in direct financial penalties. Deploying local renewable backup systems—wind, solar, or battery—improves reliability and reduces exposure to non-delivery costs.

2. Short-minute energy providers can offer cleaner and cheaper backup energy packages by switching from fossil fuels to renewables with storage. This reduces operating costs and regulatory risk.

3. National regulators and the European regulator CEER receive more accurate outage data and improved compliance reporting. This supports enforcement of delivery quality standards across regions.

4. Municipalities reduce local emissions and improve public service reliability by integrating modular renewables into their contingency planning.

5. Technology vendors access new markets for microgrids, battery systems, and automated outage response software—especially in rural areas with weak grid infrastructure.

Vertical Sector/domain

Energy (Primary Sector – Grid and Off-Grid Systems): This use case is directly situated in the energy domain. Rural grid operators, especially DSOs, face outage penalties and high operational costs from diesel-based backup systems. Deploying modular renewable-based backup (e.g. wind + battery) enhances grid stability and meets regulatory requirements such as KILE. It also supports the transition from centralised fossil-heavy assets to decentralised low-carbon resilience systems.

Manufacturing: Manufacturing facilities in rural or peri-urban areas rely on stable electricity for continuous operation. Even brief outages disrupt production and increase defect rates. Integrating smart backup systems helps manufacturers maintain uptime while reducing scope 1 emissions. Additionally, facilities can participate in demand-response schemes, creating secondary revenue streams from stored energy.

Agriculture: In agriculture, energy needs are highly seasonal (e.g. irrigation pumps, cold storage). These are often met with diesel generators in grid-weak areas. Replacing these with solar or wind-based storage systems reduces operating costs and environmental impact. It also protects agricultural output from losses due to outages and stabilises food supply chains.

Buildings and Cities: In both public and private buildings, continuity of supply is vital for elevators, safety systems, data servers, and climate control. Municipal facilities—especially in climate-sensitive regions—are increasingly integrating local energy resilience into their infrastructure. Using low-emission backup power for public buildings reduces municipal GHG footprints and aligns with climate-neutral city targets.

Health: Hospitals and clinics cannot tolerate outages. Backup power is mandated, but diesel systems create indoor and local air pollution and require frequent maintenance. Smart renewable-based backup with predictive load balancing ensures power continuity for critical care without the GHG and PM2.5 emissions associated with fossil-based systems. It also ensures quieter operation and lower lifecycle cost.

Mobility (Logistics and EV Infrastructure): Electric vehicle (EV) charging stations and logistics depots often require grid buffering to handle peak demand or operate in areas with limited grid capacity. Installing smart backup systems with storage and renewables ensures uninterrupted charging services and reduces diesel reliance in fleet operations.

Public Safety and Civil Protection: Emergency services, fire stations, and civil protection units require power reliability during crises. These actors often operate in areas where grid restoration is delayed. Deploying renewable-based emergency power units reduces logistical burden and increases readiness without GHG emissions or fuel transport dependency.

Evaluation Type of the ICT Solution:

The used ICT solution will be evaluated in a pilot type of scenario.

- Ex-ante, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution(s);

3.2.1.1.2 Source

This use case builds on insights from the GIFT project (https://www.gift-h2020.eu/), which explores ICT-based energy flexibility solutions in island and fjord-based transport systems. It focuses on managing energy loads in weak-grid areas using electric ferries, onshore batteries, and predictive control mechanisms. The Norwegian University of Science and Technology (NTNU) has been involved in systems modelling, energy performance analysis, and integration planning for such hybrid maritime-grid systems.

https://www.nve.no/reguleringsmyndigheten/publikasjoner-og-data/statistikk/avbruddsstatistikk/avbruddsstatistikk-2023/

3.2.1.1.3 Roles and Actors

The roles and actors associated with this use case are listed in the table below.

Roles:	Relationships:	Actors:
Distribution System Operators (DSOs): Maintain grid quality and report outage data (KILE/ILE).	DSOs work with ICT providers to integrate smart grid monitoring.	Hafslund, Troms Kraft Nett, and relevant municipal grid operators (potential DSOs)
Ferry Operators: Manage hybrid vessels operating on diesel-electric cycles.	Ferry operators coordinate with DSOs and battery providers for flexible charging.	Torghatten Nord (ferry operator)
ICT Solution Providers: Deliver load prediction and smart charging tools.	Regulators oversee emission compliance and delivery reliability.	ZEM (Zero Emission Maritime)
Battery System Providers: Design and deploy AC/DC + DC/DC hybrid charging infrastructure.		NTNU (willing to contribute emission modelling data)
Public Authorities and Regulators: Set emission targets, enforce delivery quality standards.		Several actors are available for consultation and data sharing under collaborative agreements.
Research Institutions (e.g., NTNU): Assess energy impact, model GHG reduction potential.		

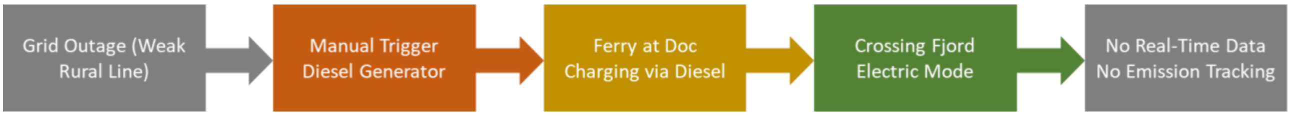
3.2.1.1.4 High level operation

3.2.1.1.4.1 High-level operations of the reference scenario

In the reference scenario, the backup energy system relies entirely on fossil fuel-based generation—typically diesel—triggered during grid outages in rural areas. This operation lacks automation, predictive analytics, or real-time control, leading to high emissions, delayed response, and inefficient fuel use.

Sequence of operations:

1. Grid outage occurs or limited capacity is detected manually or by simple fault detection.
2. Diesel generators are manually or semi-automatically activated to supply charging power to the ferry.
3. Generator supplies electricity during the outage period.
4. Ferry charges slowly while docked; redundancy systems (engine + battery) are not optimised.
5. Fuel is consumed continuously regardless of real-time load.
6. After grid restoration, the generator is shut down manually.
7. During crossing, the ferry switches to electric propulsion.
8. No real-time monitoring or predictive energy dispatch is in place, and fuel usage and performance data are logged post-event, if at all.
9. GHG emissions from diesel use are high and estimated retrospectively, often using generic emission factors[2].
10. No integration of the ferry into the local energy flexibility strategy.



[2] https://www.iea.org/data-and-statistics/data-product/emissions-factors-2024

Illustration: Reference Scenario - Diesel-Based Operation (Electric Ferry Use Case). A conventional setup where electric ferries rely on diesel while docked, with no predictive control or real-time emissions tracking. Grid outages are manually managed, and load balancing is absent.

- High GHG emissions due to continuous diesel combustion.
- No load optimisation or forecasting capability.
- Delayed response time and higher operational costs.
- No integration with grid or demand-side management.

3.2.1.1.4.2 High-level operations of the Green ICT enabled scenario

In the ICT-enabled scenario, the diesel generator is replaced or supplemented with a hybrid backup system using local renewables (e.g. wind, solar) and battery storage. An ICT control system forecasts outages, manages load, and optimises energy dispatch, reducing emissions and fuel dependency.

This scenario uses smart grid monitoring, predictive ICT tools, and hybrid AC/DC – DC/DC battery systems.

Sequence of operations:

1. Grid stability and ferry energy demand are continuously monitored using smart sensors and predictive models.
2. Predictive systems forecast grid load and optimise ferry charging windows based on historical and real-time data.
3. If an outage occurs, the control system triggers the renewable + battery setup.
4. Load is dynamically allocated based on priority and available local energy.
5. Diesel backup is used only if renewables and battery capacity are exhausted.
6. Data is logged and transmitted in real time to optimise future responses.
7. While crossing, the ferry recharges onshore battery units using a combination of a mix of renewable sources with AC/DC or DC/DC inverters/transformers, with all recharging powered by renewables.
8. Upon docking, it receives fast DC/DC charging from local storage.
9. Onboard battery-engine coordination is adjusted to minimise diesel usage.
10. All energy flows are logged in real-time, while GHG emissions are calculated periodically using the ITU-T L.1480 methodology, which provides a life cycle-based assessment framework.
11. GHG savings and ILE reductions are reported for KILE optimisation.

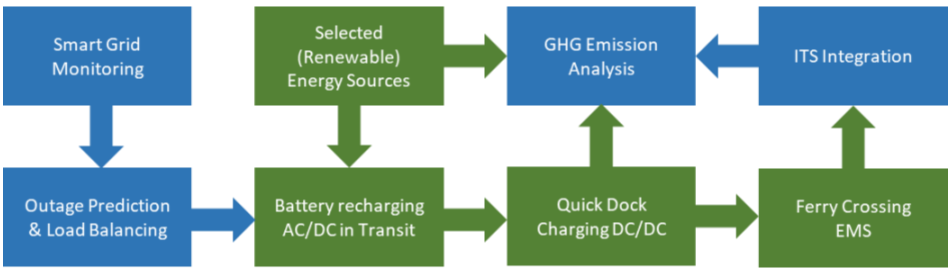


Illustration: Green ICT Scenario - Optimised Hybrid Operation (Electric Ferry Use Case). An optimised system integrating smart grid monitoring, predictive outage response, and ferry-side flexibility. The ferry supports grid load balancing by charging in transit via AC/DC, then rapidly recharging via DC/DC at the dock. Moreover, it supports operational data logging in real time, with periodic emission assessment compliant with ITU-T L.1480.

- Significant GHG reduction by prioritising renewables and battery discharge.
- Real-time control enables faster, more efficient outage response.
- Optimised fuel usage with minimal fallback on diesel generation.
- Quantifiable impact on ILE and KILE metrics, supporting regulatory compliance.

Reduces diesel use at dock: The ICT-enabled hybrid energy system significantly reduces diesel dependency during ferry docking operations by integrating predictive load balancing, onshore battery storage, and dual-mode AC/DC–DC/DC charging.

Enables flexible grid balancing: Grid reliability is improved in rural areas with weak infrastructure, lowers local GHG emissions, and supports operational data logging in real time, with periodic emission assessment compliant with ITU-T L.1480.

Supports operational data logging in real time, with periodic emission assessment compliant with ITU-T L.1480:

Additionally, it enables the ferry to function as a flexible grid asset, actively contributing to load balancing while maintaining transport reliability.

ICT solution

The ICT solution includes real-time monitoring of grid stability, predictive outage analytics, automated load dispatch management, and integration with local energy sources (wind/solar) and battery storage. It enables dynamic control of energy resources based on consumption profiles and outage probabilities.

In particular, the ICT solution is composed of:

- Sensor arrays onboard electric ferries;
- A cloud-based analytics backend;
- Real-time visual dashboards for operators;
- Edge computing units deployed at charging points;
- Integration with renewable energy data streams.

3.2.1.1.5 Willingness to work on assessment

- Yes. We are interested in working with GIE WG colleagues to complete the GHG assessment of this use case in alignment with the revised ITU-T L.1480 specification. NTNU and project partners can contribute historical and operational data, modelling inputs, and emission benchmarks.

4. Examples of GHG impact assessment of Vertical/cross-domains use cases using the revised ITU-T L.1480 recommendation

4.1 Vertical use cases

4.1.1 GHG impact assessment of “Smart Monitoring System in Windfarms” use case

This section provides GHG impact assessment of the Smart Monitoring System in Windfarms” use case using the revised ITU-T L.1480 recommendation.

A brief overview of this use case is provided in Section 3.1.1 of this report.

4.1.1.1 Introduction

This supplement illustrates the implementation of the main steps of the assessment methodology described in ITU-T Recommendation L.1480 [ITU-T L.1480]. It presents a "Tier 3" evaluation relating to an *ex-ante* case study of a project of implementing monitoring of bolts for windfarms.

4.1.1.2 Context of the study case

Since 2022, the Fraunhofer CCIT Institute [FRAUNHOFER CCIT-1] has been developing a solution for remote monitoring of bolts parameters (tightening, temperature), for which it is seeking first users and customers.

In particular, this system could be used by operators of wind farms, both offshore and onshore, as wind turbines contain numerous highly stressed bolts which need to be regularly checked during fairly lengthy maintenance operations requiring specialized personnel and equipment.

The aim of this study is to assess, to a Tier3 level of accuracy, whether the use of this remote bolt monitoring solution could reduce GHG emissions for its user, i.e. the company operating an onshore or offshore wind farm.

The following example implements the L.1480 methodology through its stages summarized in fig. 1 ("*Assessment procedure overview*") of ITU-T Recommendation L.1480 [ITU-T L.1480].

4.1.1.3 Step 1 - define the goal of the assessment

4.1.1.3.1 Define the aim and type of the assessment

The aim of this study is to apply the L.1480 methodology to assess the GHG effects of using a smart bolt monitoring solution currently under development (a pilot has been developed and is operational) for maintenance or other operations on wind turbines, both onshore and/or offshore.

The target audience is:

- potential users of the pilot solution (windfarms),
- potential suppliers for industrializing ICT solution, to develop product and offer.

The type of evaluation is a specific ICT solution, implemented in a specific context (i.e. a demonstrator, presented as a pilot system).

4.1.1.3.2 Define the assessment depth

Given that the studied project is in an initial development phase, with no identified users from whom evaluate the actual effects of the use of the solution, Tier 3 (screening / first approximation) is relevant to goal of the assessment. The Tier 3 characteristics are listed in table 2 p.13 of L.1480 [ITU-T L.1480], reproduced below in

Table 1:

Table 1: Tier3 assessment depth (L.1480)

Specification	Tier 3
Type	Screening / first approximation
Lifecycle stages	All (as material)
Data quality	Secondary (generic, proxies, averages)
ICT solution boundaries	Full life cycle
Reference scenario boundaries	Full life cycle
Data coverage and cut-off within boundaries	Proxy data used to cover data gaps. Cut-off rules apply.
Second order effects including induction	Yes
Higher order effects	Should be identified
Long term effect of any order	To be identified and reported. Considered in accordance with Tier3 rules.
Adverse environmental and social effects	To be identified and reported. Considered in accordance with Tier 3 rules.
Contextual factors	Should be identified.

4.1.1.4 Step 2 - Scoping

4.1.1.4.1 Define the ICT solution and the main second order effect

4.1.1.4.1.1 Definition of the ICT solution

The ICT solution monitors the status of bolts on the turbine, to identify loose or damaged bolts in real time.

A sensitive sensor sends the bolt pressure and temperature information to a distant monitoring station *via* an onsite gateway.

4.1.1.4.1.2 Main expected second order effect

The main expected second order effect is to reduce the onsite maintenance of bolts on wind turbine Figure 8. As this maintenance requires the turbine to be shut down Figure 7, a reduction in this downtime could increase the turbine's availability to produce energy.

In particular, this would improve the wind turbine's load factor (equal to the ratio between actual electricity production and the theoretical (i.e. nominal) maximum production over a given period): the aim is to increase the turbine's availability rate.

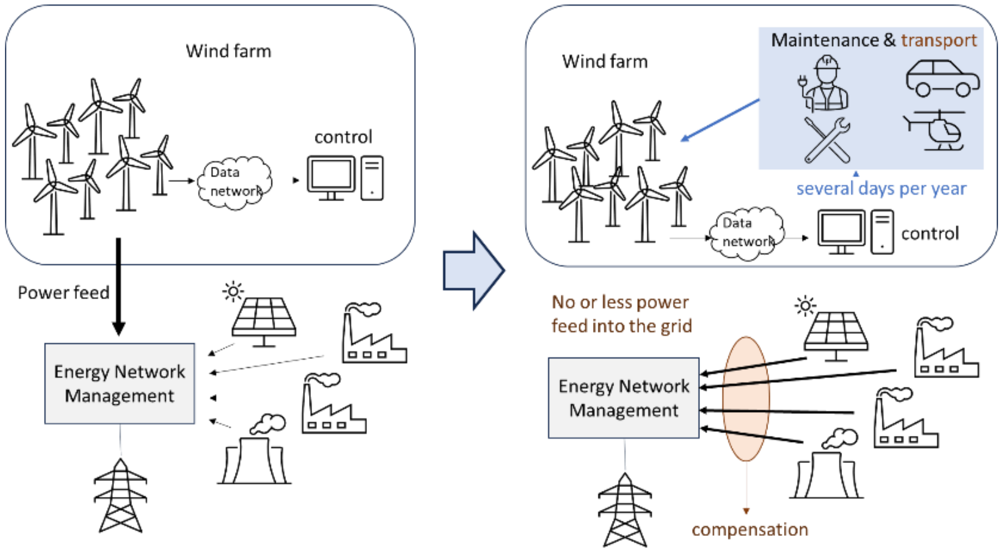


Figure 7: windfarm in operating mode/windfarm in maintenance & inspection mode

The decrease in GHG emissions generated by changes in maintenance operations would then result from Figure 8:

- the replacement of wind energy not produced during maintenance operations by energy from mixed sources available in the country where the wind turbine is located, and
- the reduction in transport to the wind farm site for maintenance and related operations.

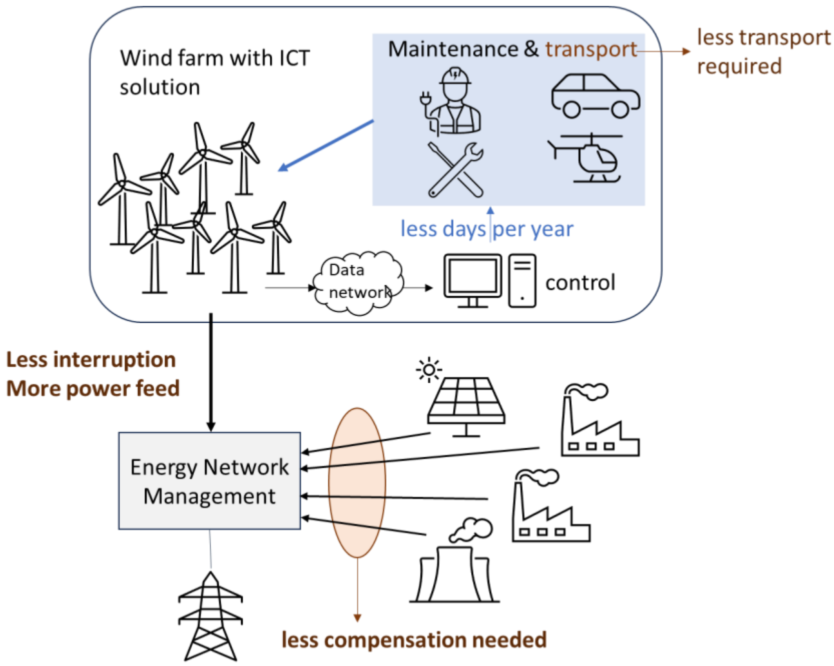


Figure 8:: main expected second order effect of use of bolt monitoring ICT solution

This bolt monitoring solution could also help prevent failures in wind turbines.

4.1.1.4.2. Define and describe the ICT solution under study

An ICT sensor is inserted inside an existing bolt; this sensor can fit in different types of bolts.

The sensor is wireless with a range of several kilometers, self-powered through light energy harvesting and can be retrofitted to existing bolt and clamp connections Figure 9.

Figure 9: bolt equipped with ICT sensor and energy harvester (photo @Fraunhofer IIS)

If an autonomous power source is required (as some wind turbine bolts are not exposed to any light), the sensor can be locally equipped with a battery that ensures data transfer while operating without having to be replaced for a period of at least 25 years.

The end-to-end ICT solution, described in [FRAUNHOFER CCIT -2], requires the following functions:

- an IoT node implemented in the bolt with energy harvester, sensors for pressure and temperature, data processing and radio transmitter,
- a gateway with data processing,
- a data transmission network,
- a monitoring application software.

The pressure sensors carry a transmitter using low data rate MIOTY [MIOTY] standard and transmits the data once per day to a gateway, also on site. This gateway then transmits the date once a day to a monitoring station and server.

4.1.1.4.3. Describe the main impact of the ICT solution on emissions in other sectors

This use of this ICT solution could reduce the emissions of the energy supplier (windfarm), by decreasing the necessary maintenance on site visits to installed wind-turbines or other effects gained thanks to the information about bolt status gathered from a distance.

4.1.1.4.4. Define the geographical and temporal coverage of the assessment

Though the designer of the ICT solution ambition is to provide smart bolt surveillance systems to installed off and onshore windmill installations anywhere in Europe, data for this *ex-ante* study was gathered from wind turbine operators in France only.

The study will therefore focus on France.

As a result of these discussions, wind turbines are certified for a 25-year service life, so the study will focus on this 25-year period.

The ICT solution of connected bolts is powered either by solar collectors, or by a thermoelectric harvester or by batteries with a 25-year lifespan if operating conditions preclude the use of the other energy sources.

4.1.1.4.5. Clarify whether the quantification of the main second order effect will be based on primary data

As the study is about a project (*ex-ante* situation), there is no primary data from actual user.

There is some data from a test bench for the energy harvester and electronics, for quantifying the first order effect.

Usage data has been gathered from interviews with potential users in charge of wind turbine field maintenance in France, both onshore and offshore.

4.1.1.4.6. Defining the functional unit

The functional unit is the use of monitoring of one wind-turbine (two cases: onshore & offshore) in France during 25 years by IoT solution checking pressure and temperature of relevant bolts on site and transmitting related data once a day.

In other terms: operating a remote bolt monitoring solution on one wind-turbine during its lifetime of 25 years, in France.

4.1.1.4.7. Defining the assessment perspective

The potential effect of the ICT solution under development is assessed.

4.1.1.4.8. Defining the composition of the ICT solution and identifying the contributors to its overall first order effects

4.1.1.4.9. The ICT bolt monitoring solution is composed of Figure 10:

a) on turbine:

- smart IoT sensor node: pressure and temperature sensors, data processing and transmitter
- energy harvester

b) on site:

- one or more MIOTY gateway(s) [MIOTY]

c) off site:

- communication network
- reporting station with agent 24/7
- data/history storage
- smart analysis program of measurements

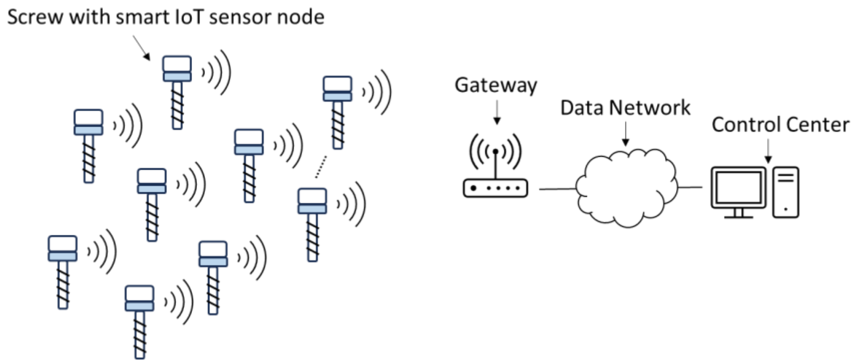


Figure 10: components of the bolt monitoring solution

4.1.1.4.10. The first order effects are shown in Table 2:

I = Immediate

D = delayed

#	Consequence	Description	I/D
1.a.1	IoT on site	turbine IoT installation (sensor + transmitter + energy harvester)	I
1.a.2	network	on site WiFi / MIOTY gateway (transmission by already equipped windfarm gateway to control center)	I
1.a.3	data center	platform off site, control center with agent 24/7, analysis program of measurements, surveillance of operations team, data/history storage	I
1.a.4	support operations	installation, as well as commercial activities	I
1.b.1	maintenance operations of ICT solution	IoT repair and replacement, off and on site if needed	D

Table 2: first-order effects

4.1.1.4.11. Identifying and defining the reference scenario

Two cases will be studied:

- onshore wind turbines,
- offshore wind turbines.

The reference scenario is the maintenance of an average wind turbine in France for 25 years, installed in 2025 without any ICT bolt monitoring solution.

The average wind turbine in France has (see Section 4.1.1.5.1 "Data collection" for data, data collection and figures used in this study):

- on land, a rated output of 2.15MWp and a load factor of 25% at installation, decreasing to 20% after 25 years,
- on the sea, a rated capacity of 7.80MWp and a load factor of 40% at installation, decreasing to 32% after 25 years.

4.1.1.4.12. Identifying additional second and higher order effects of using the ICT solution

Reminder: the main expected second order effect (generic Consequence 2a. "*evolution of wind turbines maintenance*") is the reduction in the duration of non-production of wind turbines due to maintenance, compared with the average energy mix used to compensate for this drop in production, coming from the country where the wind turbine is located or from those supplying it with energy in the case of interconnected international grids.

4.1.1.4.13. Identification of second order effects of using the ICT solution

The second order effects are Table 3:

Table 3: second-order effects

#	Consequence	Description	I/D
2.a.1.a	evolution of the time for performing an on-site wind-turbine maintenance operation	maintenance of a turbine, when carried out on site, could take a different amount of time for operators who have visited the site, for example by requiring fewer bolts to be tested individually	I
2.a.1.b	evolution of travel for performing an on-site wind-turbine maintenance operation	modifying maintenance duration on site changes the length of time teams are present on site during a maintenance campaign, and therefore affects the associated travel time.	I
2.a.2.a	evolution of the number of maintenance operation per year	the frequency of on-site maintenance visits could be modified	D
2.a.2.b	evolution of the proportion of turbines to be checked during every maintenance operation	the number of turbines in a given installation that need to be checked during on-site maintenance could be modified	D
2.b.1	evolution in the unexpected failures and breakdowns of wind-turbines	safety issue: monitoring could help prevent unexpected failure and breakdowns, thus reduce their number	D
2.b.2	modify the operating lifetime of wind-turbine	modified methods of maintenance (consisting of remote control and on-site visits mix), could lead to a change in the average service lifespan of turbines	D

I = immediate, D = delayed

4.1.1.4.14. Identification of higher order effects

The higher order effects are Table 4:

Table 4: higher-order effects

	Consequence	Description	I/D
3.a.1.a	use of financial gains or losses by solution seller (margin on sales)	the vendor of the connected solution generates operating income linked to its sales, whose gains or losses are used in other parts of its business activity	I
3.a.1.b	use of financial gains or losses by solution user	the evolution in maintenance compared to the cost of implementing and managing the ICT monitoring system generates losses or gains for the user of the solution, which he reuses elsewhere	I
3.b.1	evolution of (EU & others) rules and regulations regarding the maintenance of windfarms	contribution to maintenance of windfarms evolution, in favor of an extended use of connected bolts ICT solution	D
3.b.2	effects of the use of sensors for gathering information, other than checking bolts	use of the smart bolt monitoring installation for further purposes like environment sensing (this could increase the data volume to be processed and transferred).	D
3.b.3	development of ICT solution for extra or improved purposes	e.g. a complement of the IoT solution could include adding camera for environmental studies, thus changing the device edge and communication system to higher data rate like 5G	D
4	evolution of public confidence in wind-turbines security	(non-carbon effect)	D

I = immediate, D = delayed

Adverse environmental effects:

No adverse environmental effects of implementing the ICT solution on a wind-turbine have been identified.

4.1.1.4.15. Identification of contextual factors

Contextual factors:

F1 - Weather condition:

F1a energy production of windfarms can vary, depending on the weather conditions

F1b needs for repair and maintenance may vary according to actual usage conditions (example: destructive effects of lighting or weather preventing maintenance at a given time)

F2 - Regulatory conditions of maintenance (example: imposed maintenance rate on site)

4.1.1.4.16. Selection of effects to be quantified

Cut-off: Consequence 1.a.2. "Network: onsite WiFi / MIOTY gateway (transmission by already equipped windfarm gateway to control center)".

Once a day, the IoT solution transmits the results of its measurements on-site to the wind turbines, which are equipped with a data transmission network as soon as they are built, whether or not they are fitted with this IoT solution.

Under these conditions of use of an existing transmission network, usually of the order of 5% of the footprint of the sensor itself, just once a day for a low data flow, in view of the effects - admittedly still to be measured - relating in particular to the avoidance of electricity production, Consequence 1b. "Networks (on site gateway(s) and transmit & network between gateway and control center)" represents a tiny fraction of the GHG emissions measured for the Consequences studied, and can therefore be disregarded.

In view of the uncertainties involved in quantifying the various effects (particularly their relative magnitudes) in this ex-ante study, no further cut-offs were made.

4.1.1.4.17. Defining the system boundaries of the ICT solution scenario and the reference scenario

See **Figure 7** and Figure 8 for a diagram of maintenance operations and their effects on the availability (i.e. load factor) of wind turbines.

The identified effects and external factors are shown in the consequence tree below Figure 11:

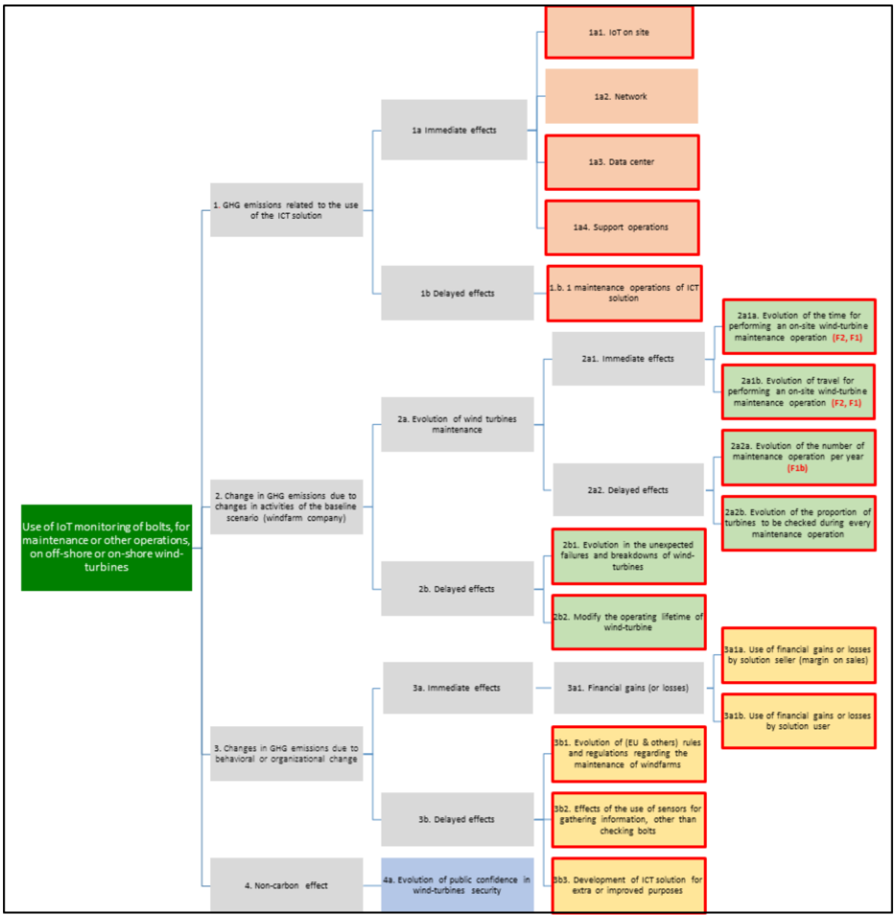


Figure 11: Consequence tree describing identified GHG emissions effects due to the use of the ICT solution.

F1: weather condition (incl. climate change)

F1a: energy production of windfarms

F1b: needs for repair and maintenance

F2: regulatory conditions of maintenance

Note: GHG emissions are always positive, but when calculating the differences, the result can be a negative or positive value.

If the result of calculation of a given Consequence, obtained by the difference between the GHG emissions of the ICT scenario and those of the reference scenario, gives a negative value, then the effects of this Consequence subtract GHG emissions in comparison with the reference scenario.

If this calculation gives a positive value, then the effects of this Consequence add GHG emissions in comparison with the reference scenario.

The sum of the calculations obtained from the assessment of each Consequence of the Consequence tree is a sum of algebraic values [ITU-T L.1480, Section 11.3.7].

4.1.1.5 Step 3 - Modelling, data collection and calculation

4.1.1.5.1 Data collection

4.1.1.5.1.1 Data collection for the reference scenario

In order to specify and quantify the reference scenario for an ex-ante study, following the preparation of an interview guide, the following were interviewed:

- an offshore wind farm operator,
- a wind farm maintenance manager with offshore and onshore experience,
- a supplier of digital twin software that can be applied to wind turbine monitoring.

The results of these three interviews are as follows:

4.1.1.5.1.1.1 Maintenance operations

i) Items maintained:

During maintenance, wind-turbines are to be checked on:

- corrosion, mold, cracks,
- bolts and bolts,
- check oil and filters (grease is sampled for analysis),
- maintenance of brakes,
- lightening protection.

ii) Bolts inspection operations Figure 12:

a) visual inspection (rust, cracks, debris, grease, coating thickness),

b) tightening to a given torque (loading, with defined torques for each diameter),

c) mark where tightened.

Some of the bolts are located in enclosed, light-free spaces.

Figure 12: check tightening torque (photo @Fraunhofer IIS)

iii) Volume:

For each wind turbine, 200 to 300 bolts have to be checked on the blades and base, + 50 on the nacelle and about 100 on the turbine (stator, shaft, generator), i.e. around 350 to 450-500 bolts per turbine.

Onshore, the anchor bolts at the foot of the turbine are also checked by hand every three years.

The machine is certified for a 25-year service life, with a maintenance program adapted to each year (year 1: 100% tightening of bolts), years 2, 3 and 4: sampling (50 to 100 bolts checked), and depending on the percentage of loose bolts found, sometimes there is a need to retighten everything.

In years 5, 10, 15 and 20 after commissioning, all bolts are retightened.

iv) Failure prevention:

The "broken bolt" problem is detected by the vibrations caused *via* a specific remote monitoring system, which makes it possible to know if this is happening.

8% of breakdowns are not dealt with remotely but require on-site intervention.

v) Network connection:

Today's wind turbines have Internet access via WiFi.

4.1.1.5.1.1.2 Frequency and duration of maintenance

Wind turbines are shut down for preventive maintenance once a year for an average period of 2.9 days (20h of work), varying up to a week depending on what the maintenance needs to check (these are different operations for each preventive maintenance, depending on the order in which the maintenance is performed).

In particular, if such preventive maintenance reveals that certain parameters have shifted, it may be necessary to repeat the maintenance until the cause is identified. In this case, over-instrumenting sometimes improves remote monitoring.

4.1.1.5.1.1.3 Maintenance process

Offshore, a shuttle boat with 3 to 4 maintenance teams on board (min. 3 people per team, max. 6 people; average 4 people), for a 45-minute trip.

Onshore, the typical trip takes 1 hour one way in a van with a team (2 people per team, max. 4 people in the turbine).

Technicians return home every evening.

4.1.1.5.1.2 Data collection for the action scenario (i.e. with ICT solution)

For the scenario with action (with ICT solution), the following elements were also indicated during these interviews:

4.1.1.5.1.2.1 Envisaged possible effects of the implementation of a connected bolt solution

i) Troubleshooting

Connected bolts won't make any difference to breakdowns, i.e. the 8% of cases that can't be handled remotely. The "broken bolt" problem is detected by vibrations, which let you know if it's happening. There is no need for another system to report if a bolt is broken. There's really no failure that could be avoided with this connected bolt solution.

Note : monitoring bolt torque should report an irregular behavior before the bolt breaks.

ii) Grease monitoring

Grease temperatures are measured, as it is an important characteristic of bearing status. This specific grease temperature sensor cannot be replaced by a measurement on a bolt, which will be less reliable. Thus, the temperature on the bolt is not very interesting, and therefore not really usable for maintenance.

iii) Sizing

To provide maintenance support, an average of 50 bolts should be connected for an onshore wind turbine, and 150 for an offshore wind turbine.

Offshore, any sensors should be installed from the outset, i.e. at the design stage: they won't be installed once the turbine is in service.

iv) Maintenance effects of ICT solution

The tightening campaign could be dispensed with if proven that the bolt torque remains within the norm (300kN at +/-5%).

In that case, this should save 30% of the maintenance time per wind turbine.

v) Certification

However, maintenance plans are certified by independent bodies: they're the ones who give the certification.

vi) Use of financial gains

The wind turbine maintenance sector is short of technicians (particularly it has to retrain from the agri-food industry): if some of them become available, they will be reused them elsewhere, without reducing nor increasing activity.

4.1.1.5.1.3 Generic data collection

In addition, the following general data were collected:

4.1.1.5.1.3.1 Wind turbine load factor

Discussion and debates:

A wind turbine produces a maximum (nominal) output; however, depending on wind conditions (and maintenance and repair periods) this output is not reached at all times Figure 13.

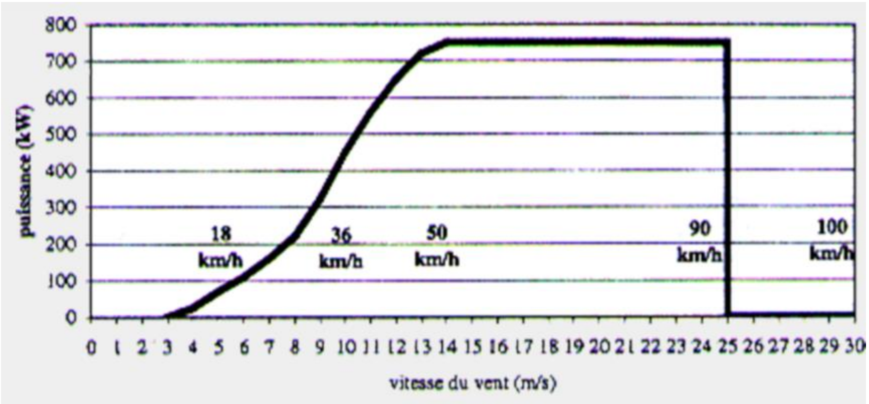


Figure 13: illustration of production as a function of wind speed (750kW wind turbine, Jeumont, France)

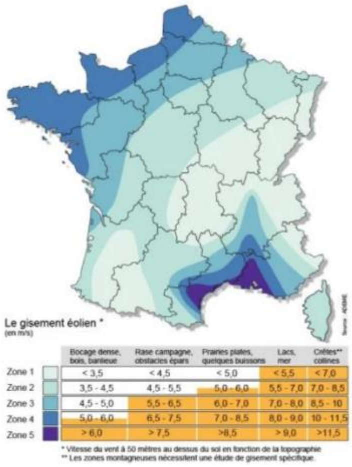
The load factor of a wind turbine is equal to the ratio between actual electricity production, and the theoretical (i.e. nominal) maximum production over a period.

Several sources provide estimates of the load factor of a wind turbine in France; a few below illustrate the diversity of the assertions:

- an average of 25.7% for French wind farms, as reported in the mainstream press [LIBERATION],
- "*A wind turbine produces as much electricity throughout the year as if it were running at maximum power for around 2,000 hours*", i.e. 2,000 / (365x24) = 22.8%, according to Mr. JANCOVICI [JANCOVICI],
- "*According to figures published by our German neighbours, the average German wind turbine has a load factor of 16.9%. In concrete terms, this means that the average German wind turbine produces only 16.9% of the electrical power for which it was designed. Worse still, a British study confirms what we feared: the wear and tear of time causes this ratio to drop by more than half in 15 years! According to Professor Gordon Hughes, author of the study, the average load factor drops from 24% in the first 12 months to 11% fifteen years later for 3,000 onshore wind turbines analysed*", according to Contrepoints magazine [CONTREPOINTS].

For offshore wind turbines, the average European load factor is 38% to 40%, according to sources [WIKIPEDIA], [VIE PUBLIQUE], [WINDEUROPE].

In addition, this load factor varies according to the location of the wind turbines and their average wind characteristics, and their performance over a given period [CONNAISSANCE DES ENERGIES -1] Figure 14:



Facteur de charge par région (%)[17]

Région	2014	2015	2016	2017	2018	2019	2020	2021	2022
Île-de-France	23,38	23,17	16,32	17,17	21,95	26,48	31,84	27,42	25,24
Auvergne-Rhône-Alpes	23,55	23,26	23,69	24,79	23,22	24,64	23,08	22,96	22,76
Occitanie	26,09	27,47	26,69	27,34	25,53	26,85	24,99	25,18	22,57
Bourgogne-Franche-Comté	18,84	23,37	21,41	21,5	22,78	25,9	26,4	24,0	22,55
Nouvelle-Aquitaine	21,84	20,21	17,33	18,33	21,95	22,53	25,23	25,48	22,49
Hauts-de-France	23,13	25,88	22,78	21,84	23,11	24,47	27,8	23,1	22,37
Pays de la Loire	22,16	23,3	20,95	20,07	21,71	23,48	26,26	23,25	22,17
Normandie	24,12	26,0	22,25	21,86	22,7	24,3	27,48	22,82	21,95
Centre-Val de Loire	22,72	25,42	22,64	21,78	21,97	24,63	27,75	24,51	21,63
Grand Est	21,13	23,89	21,24	21,22	22,65	25,12	26,96	22,03	21,46
Provence-Alpes-Côte d'Azur	26,17	24,76	24,65	26,74	23,34	24,6	19,71	23,75	20,94
Bretagne	20,0	22,45	18,96	18,72	20,74	21,29	24,28	20,33	19,29
Corse	19,86	15,34	20,83	14,19	8,4	5,84	7,14	7,6	6,16
Total France[7]	22,5	24,5	22,0	21,8	22,8	24,5	26,6	23,2	21,6

Figure 14: load factor of a wind turbine according to its location in mainland France

In addition, climate change between now and 2050 is likely to have an impact on load factors for wind turbines in France [ADEME -2] Figure 15:

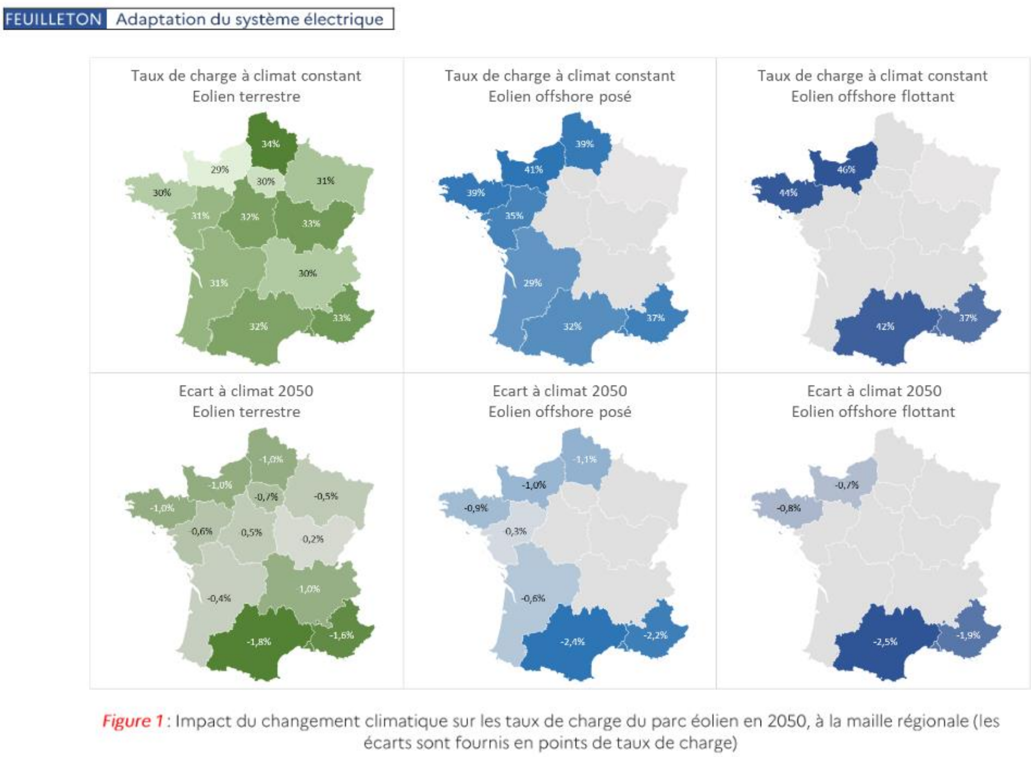


Figure 15: climate change impact on wind turbine load factor according to its location in mainland France

Finally, a specific additional interview with an experienced wind turbine maintenance manager revealed a drop in machine availability "*of a few % after year 10 or 15 or 20*".

Assumptions made:

To best reflect these disparities between different sources, the following load factors will be used in this Tier3 study:

- for onshore wind turbines, a load factor of 25% at installation, followed by linear degradation up to 25 years, bringing this factor to 20%,

- for offshore wind turbines, a load factor of 40% at installation, followed by linear degradation up to 25 years, bringing this factor to 32%.

4.1.1.5.1.3.2 Average rated power of a wind turbine (MWp)

In 2019, the average unit capacity installed offshore in France was 7.8 MWp [WINDEUROPE].

In a context where "*the exact number of wind turbines (masts) is not publicly cou*nted" [REPUBLIQUE], we can estimate that at the end of 2022 France had 9,500 wind turbines on its mainland territory totaling 20,435 MWp, i.e. an average installed power per onshore wind turbine of 2.15 MWp [CONNAISSANCE DES ENERGIES -2], [DEVELOPPEMENT DURABLE].

4.1.1.5.1.3.3 Substitution effect of wind-generated electricity

Discussion:

The substitution of wind power generation for the average electricity mix is the subject of debate:

- for some, wind power generation in France entirely replaces coal or gas generated in France or Europe [MIN. ECOLOGIE],

- for others, the intermittent nature of wind power means that conventional intermittent energies (mainly gas turbines, supplemented by coal) need to be developed to compensate for periods when wind power is not produced: "*We do have a few thermal power plants in France, which could therefore be shut down a little more often on windy days, i.e. 25 to 30% of the time at most, but that's where the benefit ends. Our thermal production is 30 to 40 TWh, so we can aim for 10 TWh of wind power at the most if we don't want to increase our peak production needs and emissions (in 2009 we're at 8, so we need to slow down!), and consequently 5 GW installed at the most*" [JANCOVICI].

Note: Installed capacity in mainland France on June 30th 2024 was 24,319 MWp, including 22,841 MWp on land and 1,476 MWp at sea, having achieved an annual 2023 production of 50,600 GW, including 1,800 GW at sea [JOURNAL EOLIEN].

Data used in this study:

For the purposes of this Tier3 study, it has been assumed that the additional wind generation made possible by the use of the ICT solution replaces electricity generated according to the average carbon emission characteristics of the French energy mix over the study period.

4.1.1.5.1.3.4 Reference situation for GHG emissions from electricity generation in France

Discussion:

In 2022, the ADEME agency evaluated several scenarios for 2050, resulting in the following evolution curves [ADEME -1] Figure 16:

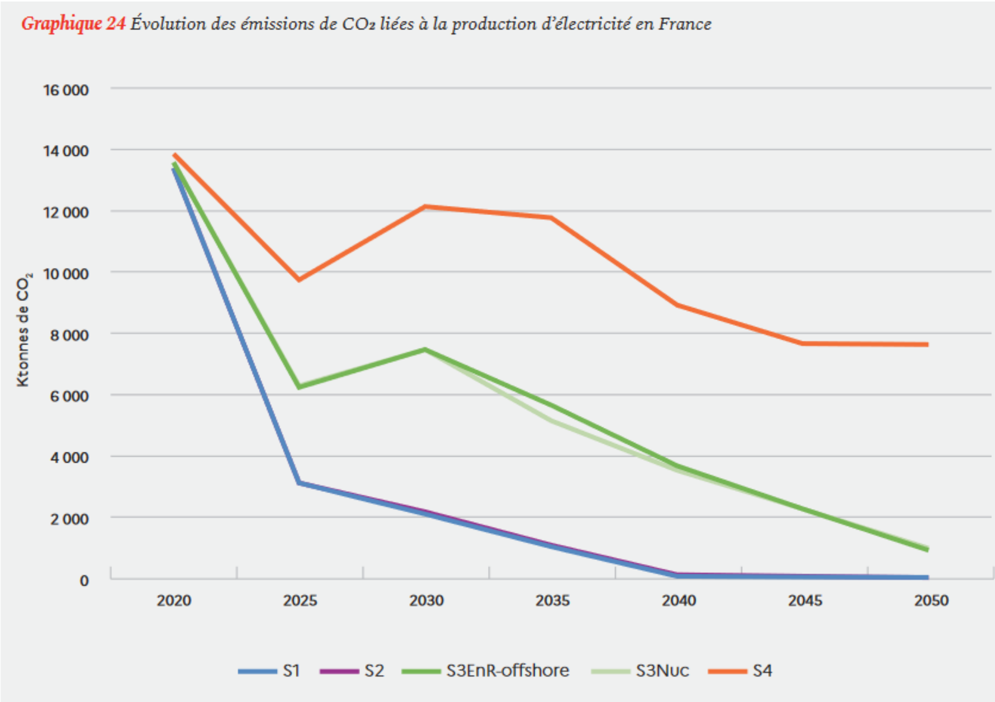


Figure 16: scenarios studied by [ADEME -1] for the decarbonization of the French electricity mix from 2020 to 2050

Note: scenario 4 describes adaptation to the effects of global warming, with no specific action on the energy mix, nor the development of low-carbon energies or the quest for sobriety in consumption and use.

Data used in this study on the decarbonization curve of the energy mix in France:

In the absence of a single assessment of the decarbonization curve of the energy mix in France between 2025 and 2049, a linear evolution linking 8000 kTonnes in 2023 to 1000 kTonnes in 2050, similar to the green curve Figure 16 "*S3EnR-offshore*", will be retained for the present Tier3 study.

Furthermore, the French electricity mix generated 32 gCO_2e per kWh produced in 2023 [RTE -1]. However, this figure should be adjusted by averaging over four years to take account of temperature variations, to 58 gCO_2e/kWh [ADEME Base Empreinte 2023, V.23.4].

4.1.1.5.2 Quantifying the first order effects

Consequence 1.a.1: IoT on site

Each sensor consists of (sensor + transmitter + energy harvester), for which the manufacturer [FRAUNHOFER CCIT -1] indicates 4.6 $kgCO_2e$ of emissions over its life cycle.

Details of the carbon footprint calculation for these devices have not been provided by the manufacturer, in particular with regard to its compliance with the requirements of Recommendation [ITU-T L.1410] on the Methodology for life cycle environmental assessments of goods, networks and services using information and communication technologies.

As the wind turbines built today have Internet access *via* WiFi, and as the study is *ex-ante*, the MIOTY Gateway [MIOTY] is not necessary. WiFi module power consumption is slightly higher than MIOTY.

To provide maintenance support, an average of 50 onshore and 150 offshore bolts would be required, installed from the outset when the wind turbine is built.

Or:

- for an onshore wind turbine: 4.6 kg x 50 = 230 kgCO_2e
- for an offshore wind turbine: 4.6 kg x 150 = 690 kgCO_2e

Consequence 1.a.2: <u>network</u>

Cut-off.

Consequence 1.a.3: <u>data center</u>

As no such center currently exists as of today for a solution that is not yet on the market, we will assume an average size for the control center, which can be adjusted as the product is marketed: a one hundred square meters of usable floor area building built to monitor around 5,000 wind turbines [ACADEMIA], with approx. 10 employees on site 24/7 (i.e. one person for every 500 wind turbines), which can be designed to receive and process data from the various control systems with which the turbines are equipped (cameras, etc.). The current study assumes that a private cloud is used.

i) Data center energy consumption

A data center of one hundred square meters [ODYSSEE] consumes 200 kWh/m²/year [ADEME Base Empreinte 2023], i.e. 200x100 = 20.000 kgCO_2e / year, for 5,000 wind turbines.

The GHG emissions of the electricity mix used in this Tier 3 assessment are taken constant here at their 2023 value, over the lifetime of the solution (25 years).

ii) Data and control center building

Construction of the control center building generates 650 kgCO_2e per m^2 of floor space (net floor area) [ADEME Base Empreinte 2023 V23.4], assuming a 30-year lifespan of that building: 650 kgCO_2e x 100m^2 / 30 years = 2,167 kgCO_2e per year, for 5,000 wind turbines.

iii) Control and data center other IT equipment

- servers: around 200 high-capacity servers per center monitoring 5,000 wind turbines on average [ACADEMIA] with a footprint of 1,500 kgCO_2e per server [ADEME Base Empreinte 2023, based on 5 times PC price], [BOAVIZTA], to be replaced every 5 years: (1,500 kgCO_2e x 200) / 5 years = 60,000 kgCO_2e per year, for 5,000 wind turbines.
- 10 monitoring displays (49") for 10 employees 24/7: 568 kgCO_2e [ADEME Base Empreinte 2023 V23.4], to be replaced every 8 years: (568 kgCO_2e x 10) / 8 years = 710 kgCO_2e per year, for 5,000 wind turbines.
- auxiliary equipment ("switch, routers, firewall"): 80.7 kgCO_2e [ADEME Base Empreinte 2023 V23.4] serving 10 servers, to be replaced every 5 years: (80.7 kgCO_2e x (200/10)) / 5 years) = 322.8 kgCO_2e per year for 5,000 wind turbines.

Total for the center's computer equipment for one wind turbine, per year: (60,000 + 710 + 322.8) = 61,032.8 kgCO_2e per year for 5,000 wind turbines.

Total for the data center: (20,000 (energy consumption) + 2,167 (building) + 61,033 (IT equipment)) = 83,200 kgCO_2e per year, for 5,000 wind turbine.

iv) Allocation according to the volume of data required for the bolt control solution only

The study focuses on a bolt control system implemented on new wind turbines, without the need for any additional remote-supervised equipment.

Under these conditions, the control center required would only control the connected bolts. Therefore, in order not to underestimate the carbon footprint linked to the use of the IoT solution, its entire footprint must be allocated to the use of the IoT solution studied although, in principle, it can also be used for other functions.

Such a data center would require just one data server for 5,000 connected turbines equipped with the IoT control system (instead of 200 servers for a center expected to receive and process 500 Mb of various data per turbine per day, including around 2.7 kb per bolt of data from the control of connected bolts, transmitted once a day).

As the ICT solution requires only one server out of 200, this proportion of the data center's GHG emissions is attributed to the bolt monitoring solution studied.

That is: 83,200 kgCO_2e / 200 = 416 kgCO_2e per year, for the data center, for 5,000 wind turbines, for the bolt control solution only.

That is, over the lifetime of the IoT solution (25 years), for a single wind turbine: 416 x 25 / 5,000 = 2.08 kgCO_2e for the data center / wind turbine.

Consequence 1.a.4: support operations

Design, marketing and sales operations are evaluated on the basis of the occupation of a sales engineer (or technician) for 5 full-time equivalent days over the 25 lifespan of the wind turbine, in monetary ratio for this Tier3 precision level study, in the absence of specific information.

Emission factor (Monetary ratios / Service - Consulting Services [ADEME Base Carbone 2023, V23.4]): 110 gCO_2 / euro of expenditure.

A full-time technician incurs an expense of 25.000 euros/year [TALENT] and is active 251 working days per year in France, i.e. for 5 days: 25.000 x (5/251) = 498 euros.

This equates to support-related emissions of 0.498 x 110 = 55 kgCO_2e.

Consequence 1.b: maintenance operations of ICT solution

The manufacturer's plan is that the bolts, a solution developed by the Fraunhofer Institute, should operate for 25 years without any maintenance, powered either by solar collectors, by thermoelectric energy harvesters and/or by batteries with a 25-year lifespan.

However, no one can guarantee that there will be no breakdowns, so for the sake of prudence, we've decided to assess a replacement of 5% of the connected bolts over 25 years, during scheduled maintenance.

Or:

- for an onshore wind turbine: 4.6 x 50 x 5% = 11.5 $kgCO_2e$,
- for an offshore wind turbine: 4.6 x 150 x 5% = 34.5 $kgCO_2e$

4.1.1.5.3 Quantify the second-order effects

Consequence 2.a.1.a: evolution of the time for performing an on-site wind-turbine maintenance operation

Interviews with experts revealed that, if the IoT system provided proof (external factor F2) recognized by regulations that the bolt torque remains within the standard (300kN at +/-5%), maintenance time could be reduced by 30%.

A wind turbine is shut down on average 2.9 days a year (20h of work) for maintenance. This average will be used for the calculation, bearing in mind that the duration varies from year to year, with the most extensive tightening operations taking place every 5 years (years 1, 5, 10, 15 and 20 after installation).

The gain in energy production time by wind turbines due to the reduction in maintenance time would therefore be 2.9 x 30% = 0.87 days / year.

Applying the linear regressions from Section 4.1.1.5.1.3.3 "Substitution effect of wind-generated electricity" between 2025 and 2049 for the French electricity mix, the onshore (resp. offshore) wind mix and the load factor, we obtain:

- for onshore wind turbines, avoided carbon emissions of 5.5T over the lifetime of the turbine Table 5:

Wind turbines																										
02-Dec-24					result of calculation		N	external data																		
Onshore wind turbines																										
Date		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Load factor (%)		25.00	24.79	24.58	24.38	24.17	23.96	23.75	23.54	23.33	23.13	22.92	22.71	22.50	22.29	22.08	21.88	21.67	21.46	21.25	21.04	20.83	20.63	20.42	20.21	20.00
Average effective production / year (MWh)		4709	4669	4630	4591	4552	4512	4473	4434	4395	4355	4316	4277	4238	4198	4159	4120	4081	4041	4002	3963	3924	3885	3845	3806	3767
Average effective production / day (MWh)		12.9	12.8	12.7	12.6	12.5	12.4	12.3	12.1	12.0	11.9	11.8	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.0	10.9	10.8	10.6	10.5	10.4	10.3
Carbon emissions from the mix. F (gCO_2e/kWh)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Onshore wind emissions F. ($kgCO_2e/MWh$)		12.64	12.16	11.67	11.18	10.70	10.21	9.72	9.24	8.75	8.27	7.78	7.29	6.81	6.32	5.83	5.35	4.86	4.38	3.89	3.40	2.92	2.43	1.94	1.46	0.97
Diff. (emissions mix F. - onshore wind) ($kgCO_2e/MWh$)		39.36	37.84	36.33	34.82	33.30	31.79	30.28	28.76	27.25	25.73	24.22	22.71	21.19	19.68	18.17	16.65	15.14	13.62	12.11	10.60	9.08	7.57	6.06	4.54	3.03
Days of wind production saved (F. rules)		0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Effective wind generation gained (MWh)		11.223	11.129475	11.03595	10.94243	10.8489	10.75538	10.66185	10.56833	10.4748	10.38128	10.28775	10.19423	10.1007	10.00718	9.91365	9.820125	9.7266	9.633075	9.53955	9.446025	9.3525	9.258975	9.16545	9.071925	8.9784
$kgCO_2e$ avoided onshore (kg)		442	421	401	381	361	342	323	304	285	267	249	231	214	197	180	164	147	131	116	100	85	70	55	41	27
Total CO_2e avoided onshore (T)	5.5																									
Production at rated power / year (MWh)		18834			F energy mix in 2023 (gCO_2e/kWh)			58	A'			Onshore wind mix F in 2023 (gCO_2e/kWh)				14.10	A''									
Average nominal wind power in France (MWh)		2.15			F energy mix in 2050 (gCO_2e/kWh)			4	B'			Onshore wind mix F in 2050 (gCO_2e/kWh)				0.97	B''									
Initial load factor (%)		25	A		Linear energy mix F			-2.000	54.000	f(-2)=A'	f(25)=B'	Linear energy mix F				-0.486	13.128	f(-2)=A''	f(25)=B''							
Load factor after 25 years (%)		20	B																							
Linear load factor over 25 years		-0.208	25.208	f(1)=A	f(25)=B	Nb h / year	8760																			

Table 5: quantification of effect 2.a.1.a) for an onshore wind turbine

- for offshore wind turbines, avoided carbon emissions of 31.0T over this lifetime Table 6:

Wind turbines																										
02-Dec-24					result of calculation		N	external data																		
Offshore wind turbines																										
Date		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Load factor (%)		40.00	39.67	39.33	39.00	38.67	38.33	38.00	37.67	37.33	37.00	36.67	36.33	36.00	35.67	35.33	35.00	34.67	34.33	34.00	33.67	33.33	33.00	32.67	32.33	32.00
Average effective production / year (MWh)		27331	27103	26876	26648	26420	26192	25965	25737	25509	25281	25054	24826	24598	24370	24143	23915	23687	23459	23232	23004	22776	22548	22320	22093	21865
Average effective production / day (MWh)		74.9	74.3	73.6	73.0	72.4	71.8	71.1	70.5	69.9	69.3	68.6	68.0	67.4	66.8	66.1	65.5	64.9	64.3	63.6	63.0	62.4	61.8	61.2	60.5	59.9
Carbon emissions from the mix. F (gCO_2e/kWh)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Offshore wind emissions F. ($kgCO_2e/MWh$)		13.99	13.45	12.91	12.37	11.83	11.30	10.76	10.22	9.68	9.14	8.61	8.07	7.53	6.99	6.46	5.92	5.38	4.84	4.30	3.77	3.23	2.69	2.15	1.61	1.08
Diff. (emissions mix F. - offshore wind) ($kgCO_2e/MWh$)		38.01	36.55	35.09	33.63	32.17	30.70	29.24	27.78	26.32	24.86	23.39	21.93	20.47	19.01	17.54	16.08	14.62	13.16	11.70	10.23	8.77	7.31	5.85	4.39	2.92
Days of wind production saved (F. rules)		0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Effective wind generation gained (MWh)		65	65	64	64	63	62	62	61	61	60	60	59	59	58	58	57	56	56	55	55	54	54	53	53	52
$kgCO_2e$ avoided offshore (kg)		2476	2361	2248	2136	2026	1917	1810	1704	1600	1498	1397	1298	1200	1104	1010	917	825	736	648	561	476	393	311	231	152
Total CO_2e avoided offshore (T)	31.0																									
Production at rated power / year (MWh)		68328			F energy mix in 2023 (gCO_2e/kWh)			58	A'			Onshore wind mix F in 2023 (gCO_2e/kWh)				15.60	A''									
Average nominal wind power in France (MWh)		7.8			F energy mix in 2050 (gCO_2e/kWh)			4	B'			Onshore wind mix F in 2050 (gCO_2e/kWh)				1.08	B''									
Initial load factor (%)		40	A		Linear energy mix F			-2.000	54.000	f(-2)=A'	f(25)=B'	Linear energy mix F				-0.538	14.524	f(-2)=A''	f(25)=B''							
Load factor after 25 years (%)		32	B																							
Linear load factor over 25 years		-0.333	40.333	f(1)=A	f(25)=B	Nb h / an	8760																			

Table 6: quantification of effect 2.a.1.a) for an offshore wind turbine

At the Tier3 level of analysis selected, the influence of weather conditions (external factor F1a) does not appear likely to significantly alter this result, especially as the study covers a 25-year period sufficient to average out such meteorological variations.

On the other hand, a catastrophic event (external factor F1b), particularly linked to climate change, leading for example to the destruction of the wind turbine itself, could alter the result.

Consequence 2.a.1.b: evolution of travel for performing an on-site wind-turbine maintenance operation

Both onshore and offshore technicians return home each evening (Section 4.1.1.5.1.1.3 "Maintenance process"), so there is one return trip to the site per day of maintenance operations.

i) Onshore, a typical daily trip takes 2 hours in a fully equipped van (about 150 km round trip), once a year.

Emission factor: 0.826 $kgCO_2e$/km driven [ADEME Base Empreinte 2023], for a light commercial vehicle (less than 3.5 tons) running on road diesel, with 7% biodiesel incorporated.

Carbon footprint of a daily round trip: 0.826x150 = 123.9 $kgCO_2e$ / maintenance day.

As on-site maintenance days are reduced by 0.87 days per year per onshore wind turbine thanks to the use of the IoT solution, GHG emissions linked to the correlative reduction in transport are reduced by: 165.2x0.87 = 144 $kgCO_2e$ / year, for an onshore wind turbine.

That is, for the 25 years studied: 123.9 x 25 = 3,098 $kgCO_2e$.

ii) Offshore, a vessel makes shuttles lasting around 45 minutes, or about 60 km, with 3 to 4 maintenance teams on board, once a year.

The footprint associated with the manufacture of the vessel is of the order of 1,720 TCO_2e ("*small bulk carrier*" category) [TEMIS], i.e. for 300 days of use per year over 25 years:

1,720,000 / (300x25) = 229.3 $kgCO_2e$ / day of use.

Its fuel-related emissions are of the order of 2.64$kgCO_2e$/km traveled, i.e.: 60x2.64 = 158.4 $kgCO_2e$ per day of use.

If the vessel is used by three teams at the same time, its GHG footprint per day of use by an offshore wind turbine maintenance team is: (158.4 + 229.3) / 3 = 129 $kgCO_2e$ / day.

As on-site maintenance days are reduced by 0.87 days per year per offshore wind turbine thanks to the use of the IoT solution, GHG emissions linked to the correlative reduction in transport are reduced by: 129x0.87 = 112 $kgCO_2e$ / year.

That is, for the 25 years studied: 112 x 25 = 2,800 $kgCO_2e$.

Consequence 2.a.2.a: <u>evolution of the number of maintenance operation per year</u>

As several operations (corrosion, mold, cracks, check oil and filters with grease sampling for analysis, brakes, lightening protection) have to be carried out during each planned maintenance, in addition to tightening bolts, the use of the IoT solution should not reduce the number of these planned maintenance operations.

Consequence 2.a.2.b: evolution of the proportion of turbines to be checked during every maintenance operation

As turbines are checked individually, and each has its own maintenance schedule, the proportion of turbines to be checked should not change as a result of using the IoT solution.

However, monitoring the tightening of bolts should in some cases enable us to identify which turbines should be visited first. However, this potential improvement in the maintenance workflow has no identified carbon impact.

Consequence 2.b.1: change in the unexpected failures and breakdowns of wind-turbines

According to experts, the IoT tracking system is unlikely to have any effect on the 8% of breakdowns that are detected and not remotely dealt with, given that the "broken bolt" problem is dealt with by the vibrations generated.

Furthermore, no breakdowns are envisaged by the experts interviewed that could be avoided by a connected bolt solution.

Consequence 2.b.2: modify the operating lifetime of wind-turbine

As the mechanical stresses on the machines remain unchanged during operation, no effect on turbine service life is envisaged, particularly in the absence of any identified effect to help prevent breakdowns.

4.1.1.5.4 Assessment of higher order effects including quantification

Although a low-level assessment (Tier3) does not strictly require the calculation of higher-order effects, it is preferable in all cases to at least assess their order of magnitude, in order to avoid omitting to take into consideration a potentially significant effect, particularly in relation to those of the second order (i.e. of an order of magnitude comparable to them).

In this *ex-ante* evaluation, given the considerable uncertainties regarding the relative orders of magnitude of the effects of using the IT solution, the higher-order effects identified will be assessed.

Consequence 3.a.1a: use of financial gains or losses by solution seller (margin on sales)

The selling price of the connected bolt, including maintenance and operation over the 25-year duration of the study, is estimated by the Fraunhofer Institute, which operates in Germany, at:

- around 200 euros per piece, depending on quantities (for a direct production cost alone of around 100 euros), and
- around 500 euros for the gateway used for a wind farm comprising up to a hundred wind turbines (i.e. 5,000 to 15,000 connected bolts).

Sales per wind turbine, including the replacement of 5% of connected pieces over 25 years (Section 4.1.1.5.2 "Quantifying the first order effects", 1.b):

- onshore with 50x1.05 bolts connected in an average field of 50 wind turbines:

52.5x200 + 500/50 = 10,510 euros,

- offshore equipped with 150x1.05 blots connected in an average field of 50 wind turbines: 157.5x200 + 500/50 = 31,510 euros.

The usual net margin for this type of mature object ("*Technology industry hardware/software hybrids*") once on a mature market is around 15% [ALEXANDER], i.e. a financial gain for the vendor per wind turbine of:

- onshore wind turbine: 10,510 x 15% = 1,577 euros,
- offshore wind turbine: 31,510 x 15% = 4,726 euros.

In the absence of information on the allocation of these benefits within the company, the average footprint for the company's sector of activity will be used.

1 euro invested in Germany in the "*Electrical and Optical Equipment*" sector generates 413g of CO_2e on average ([ITU-T L.1480 SUPPL54] [ITU-T L.1480, , Appendix IV], based on the *Guide sectoriel bilan d'émissions de gaz à effet de serre pour les activités financières*, ORSE ABC ADEME (*Greenhouse gas emissions reporting sector guide for financial activities*)).

Or:

i) emissions generated by the gains made by the seller of the solution, for an onshore wind turbine over its 25 years lifespan: 1,577 x 0.413 = 651 kgCO_2e.

ii) emissions generated by the gains made by the of the seller solution, for an offshore wind turbine over its 25 years lifespan: 4,726 x 0.413 = 1,952 kgCO2e.

Consequence 3.a.1.b:financial gains or losses by solution user

The user of the solution will save the cost of maintenance team time.

a) calculation of savings

i) For an onshore wind turbine, this means a team of 2 people and a journey and associated equipment of twice 1 hour by truck for 0.87 days.

The median salary for a wind turbine maintenance technician in France is 27,600 euros gross, representing a cost to the employer of around 50,000 euros per year for 218 working days per year [HELLOWORK].

The wage saving for the employer is therefore: (50,000÷218) x 0.87 x 2 = 400 euros.

Avoiding a 2-hour van journey (approx. 150 km travelled) immobilized for one day, the financial saving is 345 euros per day [CNR], i.e. for 0.87 days a financial saving of 300 euros.

The user of the solution thus earns (400 + 300) = 700 euros per onshore wind turbine per year.

That is, for the 25 years studied: 700 x 25 = 17,500 euros.

ii) For an offshore wind turbine a shuttle boat is used, with 3 to 4 maintenance teams on board (at sea, each team is made up of an average of 4 people), for an effective journey of 45 minutes there and back each day.

The wage saving for the employer is then: (50,000 euros ÷ 218) x 0.87 x 4 = 800 euros.

The order-of-magnitude cost of a boat transporting 25 active people for 1h30 a day can be roughly estimated at 1,000 euros, i.e. (1,000 / 3) euros per team, for 3 teams sharing this transport [LOCABOAT].

The saving is then (1,000 / 3) x 0.87 = 290 euros.

The user of the marine solution thus earns (800 + 290) = 1,090 euros per offshore turbine per year.

That is, for the 25 years studied: 1,090 x 25 = 27,250 euros.

b) assessment of the GES emissions generated by the financial gains made

i) principles for assessing GHG emissions generated by the user's financial gains

According to experts (Section 4.1.1.5.1.2.1 "Envisaged possible effects of the implementation of a connected bolt solution", vi), due to the shortage of specialized wind energy skills, the financial gains achieved will be reused to increase the number of maintenance workers, particularly coming from the agricultural sector, through retraining.

Given the significant growth forecast for wind farms in France up to 2025, the factor limiting the number of wind turbines that can be maintained by the user of the IT solution (i.e. the maintenance company) is the number of people available to be recruited.

In this way, financial gains are used to train technicians in the wind power sector, and then to hire them once they have received sufficient training (one year).

Knowledge of this precise allocation of gains enables us to assess their effect on GHG emissions ([ITU-T L. 1480 L.Sup54] §.5.1, [ITU-T L.1480 Annex IV and Section IV.2.2).

ii) calculation of GHG emissions generated by the user's financial gains

Training a technician lasts about a year (1,350 hours of training), including vacations, at a cost of around 15,000 euros [AFPA].

This means a cost to the company for this year of training of: 15,000 (training) + 50,000 (salary and charges, Section 4.1.1.5.4 "Assessment of higher order effects including quantification", consequence 3.a.1.b, a) i)) = 65,000 euros.

Once trained, the technician will be employed for the next 24 years of the study period, maintaining wind turbines.

The sum of his employment costs, excluding training, for the company will then be: 24 x 50,000 euros = 1,200,000 euros.

The financial gain for the company is distributed over the period studied in proportion to the cost of initial training period and of the period of employment:

- onshore:

17,500 euros x 65,000 / (65,000 + 1,200,000) = 899 euros for the training period,

17,500 euros x 1,200,000 / (65,000 + 1,200,000) = 16,601 euros for the period of employment.

- offshore:

27,250 euros x 65,000 / (65,000 + 1,200,000) = 1,400 euros for the training period,

27,250 euros x 1,200,000 / (65,000 + 1,200,000) = 24,850 for the period of employment.

One euro spent on training emits 0.12 kgCO_2e, and 0.17 kgCO_2e when spent on the technical maintenance of wind turbines [ADEME Base Empreinte 2023 V23.4].

Or:

- for an onshore wind turbine, over its 25-year lifetime:

899 x 0.12 + 16,601 x 0.17 = 2,882 kgCO_2e,

- for an offshore wind turbine, over its 25-year lifetime:

1,400 x 0.12 + 24,850 x 0.17 = 4,224 kgCO_2e.

Consequence 3.b.1: evolution of (EU & others) rules and regulations regarding the maintenance of windfarms

The envisaged regulatory evolution would consist in certifying the normative validity of the tightening torque (300kN at +/-5%) transmitted. This would then become equivalent to an on-site inspection, enabling the bolt monitoring solution to be used more widely to optimize maintenance operations.

Such a development is not currently underway.

It is, however, a *sine qua non* of the emission avoidance assessed in this study and would enable it to be generalized.

Consequence 3.b.2: effects of the use of sensors for gathering information, other than checking bolts

Bearing grease monitoring requires temperature measurement, which is provided by a specific sensor. As it stands, a temperature sensor on a bolt would be less reliable.

It is therefore not envisaged to use the sensors for any purpose other than bolt monitoring.

Consequence 3.b.3: development of ICT solution for extra or improved purposes

Such developments are envisaged by the solution designer. However, to date there is no visibility as to their deployment, nor their potential effect on greenhouse gas emissions.

Consequence 4: evolution of public confidence in wind-turbines security

This a non-carbon Consequence.

4.1.1.5.5 Results presentation and analysis

4.1.1.5.5.1 Results

For an onshore wind turbine Table 7, Figure 17:

	Consequence	Value ($kgCO_2e$)	%	% per order
			calculation result	
1.a.1	IoT on site	230	1.8	2.4
1.a.2	network (cut-off)	0	0.0	
1.a.3	data center	2	0.0	
1.a.4	support operations	55	0.4	
1.b.1	maintenance operations of ICT solution	12	0.1	
2.a.1.a	evolution of the time for performing an on-site wind-turbine maintenance operation (F2, F1)	-5,536	44.4	69.3
2.a.1.b	evolution of travel for performing an on-site wind-turbine maintenance operation (F2, F1)	-3,098	24.9	
2.a.2.a	evolution of the number of maintenance operation per year (F1b)	0	0.0	
2.a.2.b	evolution of the proportion of turbines to be checked during every maintenance operation	0	0.0	
2.b.1	evolution in the unexpected failures and breakdowns of wind-turbines	0	0.0	
2.b.2	modify the operating lifetime of wind-turbine	0	0.0	
3.a.1.a	use of financial gains or losses by solution seller (margin on sales)	651	5.2	28.3
3.a.1.b	use of financial gains or losses by solution user	2,882	23.1	
3.b.1	evolution of (EU & others) rules and regulations regarding the maintenance of windfarms	0	0.0	
3.b.2	effects of the use of sensors for gathering information, other than checking screws	0	0.0	
3.b.3	development of ICT solution for extra or improved purposes	0	0.0	
4	evolution of public confidence in wind turbines security	(non-carbon)	n.a.	n.a.
	Total ($kgCO_2e$)	-4,802		
	Total absolute value	12,465		

Table 7: assessment results (figures) for an onshore wind turbine in France, going into service in 2025 over its 25 years lifespan

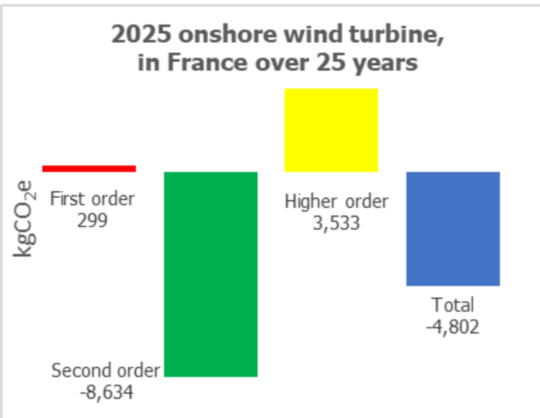


Figure 17: assessment results (graph) for an onshore wind turbine in France, going into service in 2025 over its 25 years lifespan

For an offshore wind turbine Table 8, Figure 18:

	Consequence	Value ($kgCO_2e$)	%	% per order
				calculation result
1.a.1	IoT on site	690	1.7	1.9
1.a.2	network (cut-off)	0	0.0	
1.a.3	data center	2	0.0	
1.a.4	support operations	55	0.1	
1.b.1	maintenance operations of ICT solution	35	0.1	
2.a.1.a	evolution of the time for performing an on-site wind-turbine maintenance operation (F2, F1)	-31,035	-76.1	82.9
2.a.1.b	evolution of travel for performing an on-site wind-turbine maintenance operation (F2, F1)	-2,800	-6.9	
2.a.2.a	evolution of the number of maintenance operation per year (F1b)	0	0.0	
2.a.2.b	evolution of the proportion of turbines to be checked during every maintenance operation	0	0.0	
2.b.1	evolution in the unexpected failures and breakdowns of wind-turbines	0	0.0	
2.b.2	modify the operating lifetime of wind-turbine	0	0.0	
3.a.1.a	use of financial gains or losses by solution seller (margin on sales)	1,951	4.8	15.1
3.a.1.b	use of financial gains or losses by solution user	4,224	10.4	
3.b.1	evolution of (EU & others) rules and regulations regarding the maintenance of windfarms	0	0.0	
3.b.2	effects of the use of sensors for gathering information, other than checking screws	0	0.0	
3.b.3	development of ICT solution for extra or improved purposes	0	0.0	
4	evolution of public confidence in wind turbines security	(non-carbon)	n.a.	n.a.
	Total ($kgCO_2e$)	-26,878		
	Total absolute value	40,791		

Table 8: assessment results (figures) for an offshore wind turbine in France, going into service in 2025 over its 25 years lifespan

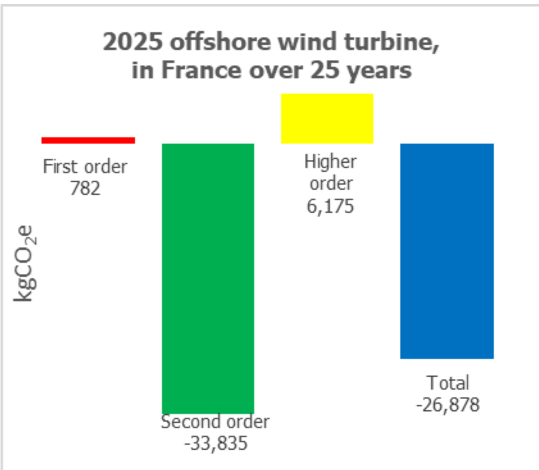


Figure 18: assessment results (graph) for an offshore wind turbine in France, going into service in 2025 over its 25 years lifespan

4.1.1.5.5.2 Analysis of results

4.1.1.5.5.2.1 Disclaimer

The present study is conducted at a "Tier3" level of precision, particularly in view of its "*ex-ante*" nature, which requires us to imagine future usage and user behavior.

Under these conditions, it should be remembered that, with regard to the scope and quality of the assessment obtained, Recommendation L.1480 states that the Tier 3 assessments "*are the simplest assessments and are not considered rigorous*" (ITU-T L.1480 Section 10.1.2), provide a « *screening / first approximation* » (ITU-T L.1480 Section 10.1.2 table 2) which "*can only give initial guidance on the effect of ICT solutions*" (ITU-T L.1480 Sections 13.3.2 and 10.5 on reporting), thus "*shall not be used for public or consumer communication*" (ITU-T L.1480 Section13.3.2) and "*should not be used as a sole input for [decision-making]*" (Note on ITU-T L.1480 Section 10.5).

With regard to the assessment process, "*the establishment of the consequence tree [is] … recommended for Tier 3 assessments* » (ITU-T L.1480 Section 10.2), and "*Tier 3 assessments should include all the effects in a consequence tree before any limitation or cut-off associated with the depth of the assessment and the chosen functional unit is performed*" (ITU-T L.1480 Section ITU-T L.1480), finally "*Tier 3 assessments shall consider net second order effects and should identify contextual factors and higher order effects. These are the simplest assessments and are not considered rigorous*" (ITU-T L.1480 Section 10.1.2).

Therefore, the figures used in this Tier3 study cannot be reused in another context and should not be used as a sole input for decision-making and all the analyses that follow are subject to the disclaimer (i.e. warnings and precautions) above.

4.1.1.5.5.2.2 Contribution to decarbonization

Subject to the above reservations (ITU-T L.1480 Section 5.5.2.1 "Disclaimer"), the use from 2025 of the IoT solution for monitoring the tightening torque of a sampling of bolts would enable a wind turbine operator in France to reduce its carbon footprint by reducing maintenance time by 30% by avoiding the need to manually check the tightening of certain bolts:

- emissions reduction of 4.8 TCO_2e over the 25-year lifetime of an onshore wind turbine,
- reduction in emissions of 26.9 TCO_2e over the 25-year lifetime of an offshore wind turbine.

4.1.1.5.5.2.3 Importance of standards and certification

However, these gains are subject to the important proviso that the measurement transmitted by the sensor is sufficiently reliable to be certified, that regulations are modified in this direction, and that such certification is obtained by the system studied, making it possible to substitute remote measurement for *in situ* measurement.

So, an essential first step seems to be the certification of the solution so that it can be used by wind farm operators in a way that reduces emissions.

4.1.1.5.5.2.4 Proportion of different effect classes

For an onshore wind turbine, the proportion in the balance on GHG emissions would be 2.4% due to the IoT solution itself (first-order effect) and 28.3% due to the reuse of financial gains (higher-order effect).

For an offshore wind turbine, the reduction in GHG emissions would be reduced by 1.9% due to the IoT solution itself (first-order effect) and by 15.1% due to the reuse of financial gains (higher-order effect).

GHG emissions linked to higher-order effects, mainly due to the reuse of the financial gains generated in economic activities, are thus between 8 and 11 times higher in both cases than those linked to the existence of the ICT solution itself.

Thus these higher-order effects cannot be neglected compared to the footprint of the ICT solution itself, in the case studied.

4.1.1.5.5.2.5 Influence of load factor evolution

The result depends on the evolution of the wind turbine load factor over time; while the load factor of a new wind turbine is the result of observation, the sources used to predict its evolution over time throughout the turbine's lifetime are imprecise and sometimes contradictory [JANCOVICI], [CONTREPOINTS], [MIN. ECOLOGIE].

In this respect, the decision to decrease this load factor to 20% (instead of 25%) after 25 years for onshore wind power, and to 32% (instead of 40%) for offshore wind power, could be conservative in terms of the decarbonization result.

By comparison, if this load factor were to remain constant over the life of the wind turbine, the result obtained (2.a.1.a effect only) would be:

- GHG emissions reduction of 5.9 TCO_2e accumulated over the 25-year lifetime of an onshore wind turbine (instead of 5.5 TCO_2e, +7%),
- GHG emissions reduction of 33.3 TCO_2e over the 25-year lifetime of a marine wind turbine (instead of 31.0 TCO_2e, +7%).
- Conversely, if this load factor were divided by a factor of 2 over the lifetime of the wind turbine [CONTREPOINTS], the result would be (2.a.1.a effect only):
- GHG emissions reduction of 4.9 TCO_2e accumulated over the 25-year lifetime of an onshore wind turbine (instead of 5.5 TCO_2e, -11%),
- GHG emissions reduction of 27.6 TCO_2e over the 25-year lifetime of a marine wind turbine (instead of 31.0 TCO_2e, -11%).

4.1.1.5.5.2.6 Uses of extra remote monitoring capabilities

When a product is not installed and in service, as is the case for the present *ex-ante* study, its capabilities and the impact of its actual use are often underestimated ("*it won't change anything*").

Therefore, it is possible - even probable - that certain consequences currently measured without carbon effect, such as the addition of temperature sensors, the use of the pressure sensor to help control elements other than bolts, or assistance with fault detection and handling, would be useful in the event of actual commissioning, naturally after a period of analysis and adaptation to the new instrumentation in order to take full advantage of the capabilities offered.

4.1.1.5.5.2.7 Effects of intermittent non-production of wind power

These effects have been assumed to be zero in the present study, due to the discrepancies noted on the subject (Section 4.1.1.5.1.3.3 "Substitution effect of wind-generated electricity").

However, if given the wind power capacity already installed in mainland France any additional wind turbine generated the installation of gas- or coal-based power generation to compensate for its intermittency, any additional wind power generation would contribute to increased GHG emissions [JANCOVICI], [CONTREPOINTS].

Under these conditions, the main second-order consequence (2.a.1.a) of using the IoT bolt control solution in France would most likely generate GHG emissions.

4.1.1.5.6 Scaling up

4.1.1.5.6.1 Additional data for scaling up

Discussion:

In a context where no public statistics on the number of wind turbines (masts) in France are published [REPUBLIQUE], we can observe that the growth in wind power production capacity in France should follow a linear progression Figure 19:

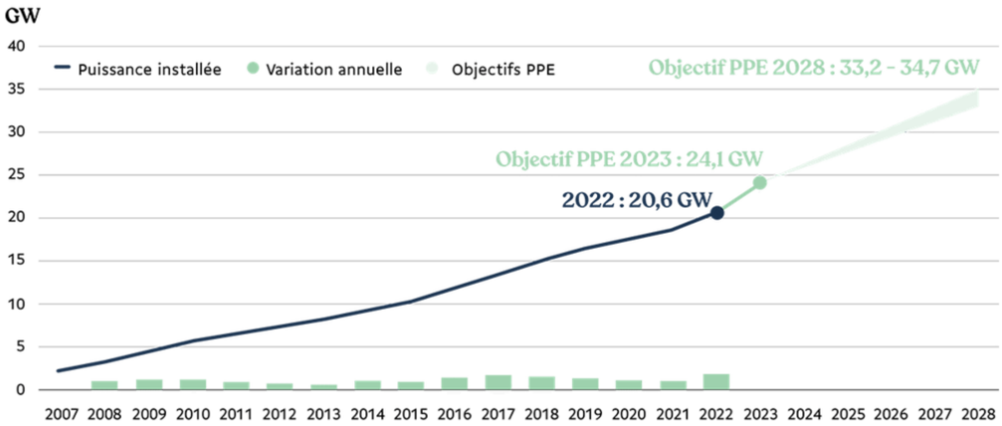


Figure 19: evolution of installed wind power capacity in France [FRANCE RENOUVELABLES]

ADEME notes that forecast growth by 2028 compared with 2022 (current PPE) is +63 to +70%, or around 9%/year growth [ADEME -2].

Wind farm production growth in 2023 was 5.9% [RTE-2], [France RENOUVELABLES -2].

In July 2024, the OpenReMap database contained 13,505 onshore and offshore wind turbines, and in January 2024 13,380 in mainland France, representing 2.04% growth in 6 months [OPENREMAP].

Data used in this study:

In view of these uncertainties and the data actually available, the present study assumes a growth rate in the number of onshore wind turbines of 6% per year over the 25-year period studied (2025 to 2049), starting from 9500 onshore wind turbines at the end of 2022 [CONNAISSANCES DES ENERGIES -2], [DEVELOPPEMENT DURABLE].

As for offshore wind turbines, 27 were in service by 2022 [ENGIE], rising to 337 by 2025 [TRANSITION ENERGETIQUE]. Beyond this date, we also assume a growth rate of 6% per year for these wind turbines.

This model does not take into account the saturation of sites for the development of offshore wind farms.

4.1.1.5.6.2 Scaling up on the French wind farm network 2025-2049

4.1.1.5.6.2.1 Results of the scaling up on the French wind farm network 2025-2049

Given these assumptions from Section 4.1.1.5.6.1 "Additional data for scaling up", if 15% of all wind turbines commissioned up to 2049 (i.e., for the last turbines installed, taking into account the use of the solution up to 2074) are equipped with the IoT remote bolt monitoring solution, the decrease in GHG emissions resulting from Consequence 2.a.1.a would be Table 9:

- -29,177 TCO_2e for onshore wind turbines,
- -5,360 TCO_2e for offshore wind turbines.

And for Consequence 2.a.1.b relating to transport:

- -16,329 TCO_2e for onshore wind turbines,
- -484 TCO_2e for offshore wind turbines.

The figures for offshore turbines reflect their smaller number than that of onshore machines.

Wind turbines																											
02-Dec-24					result of calculation		N	external data																			
Scaling up all -> 2049																											
Date		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Onshore wind turbines in production		10674.2	11315	11994	12713	13476	14284	15142	16050	17013	18034	19116	20263	21479	22767	24133	25581	27116	28743	30468	32296	34234	36288	38465	40773	43219	45812
Offshore wind turbines in production		213	337	357	379	401	425	451	478	507	537	569	604	640	678	719	762	808	856	907	962	1020	1081	1146	1214	1287	1364
Growth in onshore wind turbines			640	679	720	763	809	857	908	963	1021	1082	1147	1216	1289	1366	1448	1535	1627	1725	1828	1938	2054	2177	2308	2446	2593
Growth in offshore wind turbines			124	20	21	23	24	26	27	29	30	32	34	36	38	41	43	46	48	51	54	58	61	65	69	73	77
CO_2e avoided (T) onshore over lifetime (-> 2074)			532	564	598	633	671	712	754	800	848	898	952	1010	1070	1134	1202	1274	1351	1432	1518	1609	1706	1808	1916	2031	2153
CO_2e avoided (T) offshore over lifetime (-> 2074)			577	94	100	106	112	119	126	134	142	150	159	169	179	189	201	213	226	239	253	269	285	302	320	339	360
CO_2e avoided (T) onshore transport			298	315	334	354	376	398	422	448	474	503	533	565	599	635	673	713	756	801	850	900	955	1012	1072	1137	1205
CO_2e avoided (T) offshore transport			52	8	9	10	10	11	11	12	13	14	14	15	16	17	18	19	20	22	23	24	26	27	29	31	32
Total CO_2e avoided onshore (T) ->2074, sub. + trans	45506																										
Total CO_2e avoided offshore (T) ->2074, sub. + trans	5844		Total CO_2e avoided sub. onshore (T) until 2074				29177			Total CO_2e avoided (T) onshore transport				16329													
Onshore transport / 25 years (kgCO_2e)	3098		Total CO_2e avoided sub. offshore (T) until 2074				5360			Total CO_2e avoided (T) offshore transport				484													
Offshore transport / 25 years (kgCO_2e)	2800		ICT solution equipment rate (%)			15	Variable			Annual growth rate of installed base (%)				6													
Onshore wind turbines in 2022	9500		https://www.connaissancedesenergies.org/fiche-pedagogique/parc-eolien-francais								https://www.statistiques.developpement-durable.gouv.fr/publicationweb/526																
Date		2022	2023	2024	2025		https://www.engie.com/news/eolien-offshore-en-mer-france																				
Offshore wind turbines		27	142	213	337		https://transition-energetique.eco/combien-eolienne-france/																				

Table 9: 2.a.1.a & 2.a.1.b evaluation results after scaling up, all until 2049

As the first-order and higher-order effects have been calculated per turbine per year, they can also be scaled according to the number of turbines commissioned each year featuring the IoT solution (i.e. 15%) Table 10.

Wind turbines																											
02-Dec-24																											
Scaling up all -> 2049 1st & higher order					result of calculation		N	external data																			
Date		2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Growth in onshore wind turbines			640	679	720	763	809	857	908	963	1021	1082	1147	1216	1289	1366	1448	1535	1627	1725	1828	1938	2054	2177	2308	2446	2593
Growth in offshore wind turbines			124	20	21	23	24	26	27	29	30	32	34	36	38	41	43	46	48	51	54	58	61	65	69	73	77
First order onshore (kgCO_2e)			28684	30405	32229	34163	36213	38386	40689	43130	45718	48461	51369	54451	57718	61181	64852	68743	72867	77239	81874	86786	91993	97513	103364	109565	116139
Higher order onshore (kgCO_2e)			339408	359772	381358	404240	428494	454204	481456	510343	540964	573422	607827	644297	682955	723932	767368	813410	862215	913947	968784	1026911	1088526	1153838	1223068	1296452	1374239
First order offshore (kgCO_2e)			14537	2371	2513	2664	2823	2993	3172	3363	3564	3778	4005	4245	4500	4770	5056	5360	5681	6022	6383	6766	7172	7603	8059	8542	9055
Higher order offshore (kgCO_2e)			114855	18729	19853	21044	22306	23645	25063	26567	28161	29851	31642	33540	35553	37686	39947	42344	44885	47578	50432	53458	56666	60066	63670	67490	71539
ref. first order onshore (kgCO_2e)	299		Total first order onshore (TCO_2e)			1574																					
ref. higher order onshore (kgCO_2e)	3,533		Total higher order onshore (TCO_2e)			18621																					
ref. first order offshore (kgCO_2e)	782		Total first order offshore (TCO_2e)			135																					
ref. higher order offshore (kgCO_2e)	6,175		Total higher order offshore (TCO_2e)			1067																					
ICT solution equipment rate (%)	15	Variable																									

Table 10: first and higher order evaluation results after scaling up, all until 2049

The decrease in GHG emissions resulting from the use of the ICT IoT solution in the wind turbine lifetime equipped (15% of turbines) commissioned between 2025 and 2049 in France, over the duration of the wind turbine lifetime (25 years) would then be:

(-29,177 + (-16,329) + 1,574 + 18,621) = -25,311 TCO_2e for onshore wind power,

(-5,360 + (-484) + 135 + 1067) = -4,642 TCO_2e for offshore wind power.

Analysis and criticism of the scaling result for French wind farms

This scaling calculation is open to criticism in that it takes as a reference an installation without an IoT solution, whereas IoT solutions (15% of the market) could already be commonplace before 2049.

It is also open to criticism in that the evolution of the French electricity mix between 2025 and 2049 is used uniformly as the reference situation, whereas electricity production from wind turbines commissioned after 2025 should be compared in part with the French electricity mix after 2049.

This inaccuracy can be significant: for example, if the production of a wind turbine installed in 2025 avoids 230 kgCO_2e/MW produced over its lifetime (i.e. until 2049), the electricity production of the same wind turbine installed in 2049 will only avoid 2.24x25 = 56 kgCO_2e/MW from 2049 to 2074 if emissions from the French electricity mix remain stable from 2049 onwards.

4.1.1.5.6.3 Case study results: user and ICT solution

For these reasons, it would be more appropriate to scale up the ICT solution to the wind farm in question, either from a commercial point of view or in terms of the intended user.

4.1.1.5.6.3.1 Scaling up over one year

For example, equipping 15% of new turbines installed in France in 2025 would lead to a decrease in GHG emissions resulting from Consequence 2.a.1.a summed up to 2049 of Table 11:

- -532 TCO_2e for onshore wind turbines,
- -577 TCO_2e for offshore wind turbines.
- And for Consequence 2.a.1.b relating to transport:
- -298 TCO_2e for onshore wind turbines,
- -52 TCO_2e for offshore wind turbines.

Wind turbines					
02-Dec-24		result of calculation			
Scaling up 2025 only	N	external data			
Date		2025			
Growth in onshore wind turbines		640			
Growth in offshore wind turbines		124			
CO_2e avoided (T) onshore over lifetime (-> 2074)		**532**			
CO_2e avoided (T) offshore over lifetime (-> 2074)		**577**			
CO_2e avoided (T) onshore transport		**298**			
CO_2e avoided (T) offshore transport		**52**			
Total CO_2e avoided onshore (T) until 2049	**829**				
Total CO_2e avoided offshore (T) until 2049	**629**				
Onshore transport / 25 years (kgCO_2e)	**3098**	CO_2e avoid onshore subs. (kgCO_2e)			5536
Offshore transport / 25 years (kgCO_2e)	**2800**	CO_2e avoid offshore subs. (kgCO_2e)			31035
ICT solution equipment rate (%)	**15**	Variable			

Table 11: 2.a.1.a & 2.a.1.b evaluation results case study "user and ICT solution": scaling up 2025 only, over the 25 years lifespan of turbines installed in 2025

As the first-order and higher-order effects have been calculated per turbine per year, they can also be scaled according to the number of turbines commissioned in 2025 featuring the IoT solution (i.e. 15%) Table 12.

Wind turbines					
02-Dec-24		result of calculation			
Scaling up 2025 only	N	external data			
Date			2025		
Growth in onshore wind turbines			640		
Growth in offshore wind turbines			124		
ref. first order onshore ($kgCO_2e$)	299	Total first order onshore (TCO_2e)			29
ref. higher order onshore ($kgCO_2e$)	3,533	Total higher order onshore (TCO_2e)			339
ref. first order offshore ($kgCO_2e$)	782	Total first order offshore (TCO_2e)			15
ref. higher order offshore ($kgCO_2e$)	6,175	Total higher order offshore (TCO_2e)			115
ICT solution equipment rate (%)	15	Variable			

Table 12: first and higher order evaluation results after scaling up, on the year 2025 only, over the 25 years lifespan of turbines installed in 2025

The decrease in GHG emissions resulting from the use of the ICT IoT solution in the wind turbine lifetime equipped (15% of turbines) commissioned in 2025 in France, over the duration of the wind turbine lifetime (25 years) would then be Table 12:

(-532 + (-298) + 29 + 339) = -462 TCO_2e for onshore wind turbine,

(-577 + (-52) + 15 + 115) = -499 TCO_2e for offshore wind turbine.

4.1.1.5.6.3.2 Study with an identified user

A study, even an *ex-ante* one, with an identified user would enable to refine the result according to the specific characteristics of the wind farm installations, in particular:

- the average installed turbine power (Section 4.1.1.5.1.3 Generic data collection),
- the load factor according to turbine type and geographical location (wind characteristics) and its evolution over time, including climate change (Section 4.1.1.5.1.3 Generic data collection, Figure 14 and Figure 15),
- the life cycle of turbines and equipment, depending on how they are installed (including the carbon footprint of the passive part, for example decreased by using cement without clinker and/or reducing its volume at the wind-turbine base) (Section 4.1.1.5.1.3.4 "Reference situation for GHG emissions from electricity generation in France ii"),
- the control center, associated data transmission and support operations (Section 4.1.1.5.2 "Quantifying the first order effects"),
- the reduction in maintenance time enabled by IoT control of bolts, always on condition that standardization allows this beforehand (Section 4.1.15.1.2.1 "Envisaged possible effects of the implementation of a connected bolt solution", iv and v).

4.1.1.5.6.4 General application cases

4.1.1.5.6.4.1 General case for reducing wind turbine maintenance time

The present study could also be used to evaluate, still from a low precision Tier3 perspective, the effects on GHG emissions of any action to reduce the duration of wind turbine maintenance, and more generally to increase wind turbine uptime (i.e. turbine load factor improvement).

4.1.1.5.6.4.2 Application of the assessment to wind power generation

It is also possible to apply the assumptions and methodology of the present assessment at Tier3 level of accuracy, to the measurement of the decarbonization effect of wind power in general.

Thus, by retaining the assumptions (some of which are controversial) used in the present Tier3 study, in particular:

- the decarbonization of the French electricity mix (Section 4.1.1.5.1.3.4 “Reference situation for GHG emissions from electricity generation in France” and Figure 16)
- the wind load factor and its evolution over time (Section 4.1.1.5.1.3.1 “Wind turbine load factor”),
- the contribution of wind power generation to decarbonization (Section 4.1.1.5.1.3.3 “Substitution effect of wind-generated electricity”),

an average wind turbine installed in France in 2025, over the 25 years of its operation, would make it possible to avoid:

- for an onshore wind turbine Table 13: 2,322 TCO_2e,
- for an offshore wind turbine Table 14: 13,020 TCO_2e.

Wind turbines													
10-Dec-24					result of calculation		N	external data					
Onshore wind turbines													
Date		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Years		1	2	3	4	5	6	7	8	9	10	11	12
Load factor (%)		25.00	24.79	24.58	24.38	24.17	23.96	23.75	23.54	23.33	23.13	22.92	22.71
Average effective production / year (MWh)		4709	4669	4630	4591	4552	4512	4473	4434	4395	4355	4316	4277
Carbon emissions from the mix. F (gCO_2e/kWh)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00
Onshore wind emissions F. ($kgCO_2e/MWh$)		12.64	12.16	11.67	11.18	10.70	10.21	9.72	9.24	8.75	8.27	7.78	7.29
Diff. (emissions mix F. - onshore wind) ($kgCO_2e/MWh$)		39.36	37.84	36.33	34.82	33.30	31.79	30.28	28.76	27.25	25.73	24.22	22.71
$kgCO_2e$ avoided onshore (kg)		185320	176707	168214	159839	151582	143445	135426	127526	119745	112083	104540	97115
Total CO_2e avoided onshore (T)	2322.4												
Production at rated power / year (MWh)		18834			F energy mix in 2023 (gCO_2e/kWh)			58	A'			Onshore wind mix F in 2023 (gCO_2e/kWh)	
Average nominal wind power in France (MWh / an)		2.15			F energy mix in 2050 (gCO_2e/kWh)			4	B'			Onshore wind mix F in 2050 (gCO_2e/kWh)	
Initial load factor (%)		25	A		Linear energy mix F			-2.000	54.000	f(-2)=A'	f(25)=B'	Linear energy mix F	
Load factor after 25 years (%)		20	B										
Linear load factor over 25 years		-0.208	25.208	f(1)=A	f(25)=B	Nb h / year	8760						

Date	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years	13	14	15	16	17	18	19	20	21	22	23	24	25
Load factor (%)	22.50	22.29	22.08	21.88	21.67	21.46	21.25	21.04	20.83	20.63	20.42	20.21	20.00
Average effective production / year (MWh)	4238	4198	4159	4120	4081	4041	4002	3963	3924	3885	3845	3806	3767
Carbon emissions from the mix. F (gCO_2e/kWh)	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Onshore wind emissions F. ($kgCO_2e/MWh$)	6.81	6.32	5.83	5.35	4.86	4.38	3.89	3.40	2.92	2.43	1.94	1.46	0.97
Diff. (emissions mix F. - onshore wind) ($kgCO_2e/MWh$)	21.19	19.68	18.17	16.65	15.14	13.62	12.11	10.60	9.08	7.57	6.06	4.54	3.03
$kgCO_2e$ avoided onshore (kg)	89809	82622	75554	68604	61773	55061	48468	41994	35638	29402	23284	17285	11404
Production at rated power / year (MWh)			14.10	A''									
Average nominal wind power in France (MWh / an)			0.97	B''									
Initial load factor (%)			-0.486	13.128	f(-2)=A''	f(25)=B''							

Table 13: calculation of the effect on GHG emissions of substituting the energy produced by an average onshore wind turbine in France installed in 2025 over its 25-year lifetime, with energy produced according to the average energy mix in France over the period

Wind turbines													
10-Dec-24					result of calculation		N	external data					
Offshore wind turbines													
Date		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Years		1	2	3	4	5	6	7	8	9	10	11	12
Load factor (%)		40.00	39.67	39.33	39.00	38.67	38.33	38.00	37.67	37.33	37.00	36.67	36.33
Average effective production / year (MWh)		27331	27103	26876	26648	26420	26192	25965	25737	25509	25281	25054	24826
Carbon emissions from the mix. F (gCO_2e/kWh)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)		52.00	50.00	48.00	46.00	44.00	42.00	40.00	38.00	36.00	34.00	32.00	30.00
Offshore wind emissions F. ($kgCO_2e/MWh$)		13.99	13.45	12.91	12.37	11.83	11.30	10.76	10.22	9.68	9.14	8.61	8.07
Diff. (emissions mix F. - offshore wind) ($kgCO_2e/MWh$)		38.01	36.55	35.09	33.63	32.17	30.70	29.24	27.78	26.32	24.86	23.39	21.93
$kgCO_2e$ avoided offshore (kg)		1038963	990677	943058	896105	849818	804197	759242	714953	671330	628373	586081	544456
Total CO_2e avoided offshore (T)	13020.3												
Production at rated power / year (MWh)		68328			F energy mix in 2023 (gCO_2e/kWh)			58	A'			Onshore wind mix F in 2023 (gCO_2e/kWh)	
Average nominal wind power in France (MWh / an)		7.8			F energy mix in 2050 (gCO_2e/kWh)			4	B'			Onshore wind mix F in 2050 (gCO_2e/kWh)	
Initial load factor (%)		40	A		Linear energy mix F			-2.000	54.000	f(-2)=A'	f(25)=B'	Linear energy mix F	
Load factor after 25 years (%)		32	B										
Linear load factor over 25 years		-0.333	40.333	f(1)=A	f(25)=B	Nb h / an	8760						

Date	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Years	13	14	15	16	17	18	19	20	21	22	23	24	25
Load factor (%)	36.00	35.67	35.33	35.00	34.67	34.33	34.00	33.67	33.33	33.00	32.67	32.33	32.00
Average effective production / year (MWh)	24598	24370	24143	23915	23687	23459	23232	23004	22776	22548	22320	22093	21865
Carbon emissions from the mix. F (gCO_2e/kWh)	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Carbon emissions from the mix. F ($kgCO_2e/MWh$)	28.00	26.00	24.00	22.00	20.00	18.00	16.00	14.00	12.00	10.00	8.00	6.00	4.00
Offshore wind emissions F. ($kgCO_2e/MWh$)	7.53	6.99	6.46	5.92	5.38	4.84	4.30	3.77	3.23	2.69	2.15	1.61	1.08
Diff. (emissions mix F. - offshore wind) ($kgCO_2e/MWh$)	20.47	19.01	17.54	16.08	14.62	13.16	11.70	10.23	8.77	7.31	5.85	4.39	2.92
$kgCO_2e$ avoided offshore (kg)	503497	463204	423577	384616	346321	308692	271729	235432	199800	164835	130536	96903	63936
Production at rated power / year (MWh)			15.60	A''									
Average nominal wind power in France (MWh / an)			1.08	B''									
Initial load factor (%)			-0.538	14.524	f(-2)=A''	f(25)=B''							

Table 14: calculation of the effect on GHG emissions of substituting the energy produced by an average offshore wind turbine in France installed in 2025 over its 25-year lifetime, with energy produced according to the average energy mix in France over the period

4.1.1.6 Step 4 - Interpretation of results

4.1.1.6.1 Evaluation of the applied method

The Tier3 level of precision described in Recommendation L.1480 has been applied, as is natural for an *ex-ante* evaluation in which, by definition, the uses of the ICT solution are not known with any precision, and even more so in the case of a new solution which is not active with any customer/user of the type studied (i.e. wind farm manager).

4.1.1.6.2 Data quality analysis

Data relating to use by wind turbine maintainers has been obtained from qualified and experienced experts. They can be considered sufficient and reliable for the desired Tier3 level of analysis.

Generic data were obtained from various sources and available literature. They range from precise, factual data (e.g. energy production from wind turbines in France in 2023) to controversial elements whose effective measurement would undoubtedly be complex (e.g.

substitution of injected energy quantities for the average energy mix, or evolution over time of a wind turbine's load factor).

4.1.1.6.3 Sensitivity analysis

The result depends entirely on the existence of standardization that recognizes the possibility of using data received from the IoT sensor to reduce maintenance checks (tightening torque).

It is also highly dependent on:

- changes in the wind turbine's load factor as it ages,
- the decarbonization of the electricity mix in the geographical area under consideration over the lifetime of the wind turbine. As an example, if the study had been carried out in Germany, considering that the maintenance uses of wind turbines are comparable, it would have been necessary to consider the evolution of the German electricity mix,
- the effectiveness (or otherwise) of the decarbonizing effect of wind power generation, given that it requires other means of power generation to compensate for its intermittent nature.

4.1.1.6.4 Uncertainty analysis

The result depends entirely on a subject outside the scope of standard L.1480 [ITU-T L.1480], i.e. the ability (or otherwise) of wind generation to effectively substitute for electricity produced with a higher CO_2e per MWh rate (see above Section 4.1.1.5.1.3 "Generic data collection" iii) [JANCOVICI], [CONTREPOINTS].

The evolution of the load factor over time must be considered imprecise at this stage.

Lastly, estimates of the scaling-up of French wind farms are purely indicative, and overestimated due to the reference situation used (Section 4.1.1.5.6.2 "Scaling up on the French wind farm network 2025-2049").

4.1.1.7 Step 5 - Reporting

The current ITU-T publication reports on this study, which has been drawn up with this distribution in mind.

4.1.1.8 Step 6 - Critical review

This document has been reviewed by the members of the joint working group between the European Telecommunications Standards Institute (ETSI) and the Working Group 9 of ITU-T Question 5: "*Climate change and assessment of digital technologies in the framework of the Sustainable Development Goals and the Paris Agreement*".

4.1.1.9 References for use case "Smart Monitoring System in Windfarms"

[ITU-T L.1480] https://www.itu.int/rec/T-REC-L.1480

[FRAUNHOFER CCIT -1] https://www.cit.fraunhofer.de/

[FRAUNHOFER CCIT -2] https://www.cit.fraunhofer.de/en/tech-hubs/iot-comms/q-bo.html

[ITU-T L.1410] https://www.itu.int/rec/T-REC-L.1410

[MIOTY] https://mioty-alliance.com/

[ACADEMIA] https://www.academia.edu/91428601/Wind_control_centres_State_of_the_art

[ODYSSEE] https://www.odyssee-mure.eu/publications/efficiency-by-sector/services/offices-specific-energy-and-electricity-consumption.html

[BOAVIZTA] https://boavizta.org/blog/empreinte-de-la-fabrication-d-un-serveur

[TALENT] https://fr.talent.com/salary

[TEMIS] https://temis.documentation.developpement-durable.gouv.fr/docs/Temis/0059/Temis-0059657/16878.pdf

[LIBERATION] https://www.liberation.fr/checknews/est-il-vrai-que-les-eoliennes-fonctionnent-seulement-25-du-temps-comme-laffirme-stephane-bern-20210602_4OTLBNG25FBCPBUN3GJIHFIAXI/

[JANCOVICI] https://jancovici.com/transition-energetique/renouvelables/pourrait-on-alimenter-la-france-en-electricite-uniquement-avec-de-leolien/

[CONTREPOINTS] https://www.contrepoints.org/2014/02/16/156807-bilan-carbonne-eoliennes-vraie-situation-scientifique

[WIKIPEDIA] https://fr.wikipedia.org/wiki/%C3%89olienne_en_mer , mentioning [WINDEUROPE]

[WINDEUROPE] https://windeurope.org/

[VIE PUBLIQUE] https://www.vie-publique.fr/parole-dexpert/283638-quel-developpement-des-eoliennes-debat-paul-neau-et-gregoire-souchay

[CONNAISSANCE DES ENERGIES -1] https://www.connaissancedesenergies.org/fiche-pedagogique/eoliennes-terrestres ; https://fr.wikipedia.org/wiki/%C3%89nergie_%C3%A9olienne_en_France

[ADEME -2] https://librairie.ademe.fr/ged/7881/feuilleton-adaptation-systeme-elec-CC-transitions2050-ademe.pdf

[REPUBLIQUE] https://www.lanouvellerepublique.fr/a-la-une/infographies-l-eolien-dans-votre-region-et-en-france

[CONNAISSANCE DES ENERGIES -2], https://www.connaissancedesenergies.org/fiche-pedagogique/parc-eolien-francais

[DEVELOPPEMENT DURABLE] https://www.statistiques.developpement-durable.gouv.fr/publicationweb/526

[MIN. ECOLOGIE], https://www.ecologie.gouv.fr/sites/default/files/documents/21088_VraiFaux_E%CC%81olien_terrestre%20(1).pdf

[JOURNAL EOLIEN] https://www.journal-eolien.org/tout-sur-l-eolien/la-puissance-eolienne-en-france-2 /

[ADEME-1] https://librairie.ademe.fr/ged/6843/feuilleton_mix_electrique_transitions2050_ademe.pdf

[RTE -1] https://analysesetdonnees.rte-france.com/bilan-electrique-2023/emissions#Introduction

[ADEME Base Empreinte 2023] https://base-empreinte.ademe.fr/

[HELLOWORK] https://www.hellowork.com/fr-fr/salaires/technicien-de-maintenance-eolien.html

[CNR] https://www.cnr.fr/formule-trinome

[LOCABOAT] https://www.locaboat.com/location-bateau-groupe/

[ITU-T L.1480 L.Sup54] https://www.itu.int/rec/T-REC-L.Sup54/en

[AFPA] https://www.afpa.fr/formation-qualifiante/technicien-superieur-de-maintenance-d-eoliennes-1

[ALEXANDER] https://www.alexandergroup.com/insights/manufacturing-iot-offers-greater-revenue-and-complexity/

[FRANCE RENOUVELABLES - 1] https://www.france-renouvelables.fr/eolien-terrestre/

[ADEME-2] https://librairie.ademe.fr/ged/8006/Eolien-terrestre-012221-7.pdf

[RTE-2] https://assets.rte-france.com/prod/public/2024-03/2024-03-29-panorama-electricite-renouvelable-2023.pdf

[France RENOUVELABLES - 2] https://www.france-renouvelables.fr/etudes-et-publications/observatoire-de-leolien-2024/

[OPENREMAP] https://www.remapservices.com/fr/news/2024-01-16-eolien-terrestre-capacite-installee-par-region-janvier-2024

[ENGIE] https://www.engie.com/news/eolien-offshore-en-mer-france

[TRANSITION ENERGETIQUE] https://transition-energetique.eco/combien-eolienne-france/

4.1.2 GHG impact assessment of "Visual inspection for automated Product Quality assessment" use case

The study aims to evaluate, at a Tier 3 level of precision, the extent to which an automated quality assurance system can diminish greenhouse gas emissions for its users. This example follows the L.1480 approach as stated in its steps, shown in Figure 1 ("Assessment Procedure Overview") of ITU-T Recommendation L.1480 [ITU-T L.1480].

This section provides a GHG impact assessment of the visual inspection for the automated Product Quality assessment use case using the revised ITU-T L.1480 recommendation.

A brief overview of this use case is provided in Section 3.1.2 of this report, and depicted in Figure 5 (a) – the Ethernet switch based solution.

4.1.2.1 Introduction

This supplement illustrates the implementation of the main steps of the assessment methodology described in ITU-T Recommendation L.1480 [ITU-T L.1480]. It presents a "Tier 3" evaluation relating to an *ex-ante* case study of a project of visual inspection for an automated Product Quality assessment study case.

4.1.2.2 Step 1 - Define the goal of the assessment

4.1.2.2.1 Define the aim and type of the assessment

The study aims to promote a sustainable and eco-friendly ICT industry by fostering the development of secure and trustworthy autonomous networking solutions. The purpose of the case study is to evaluate the GHG emissions linked to the deployment of an Ethernet switch-based ICT solution by comparing it with a traditional human-based Quality Assurance system.

Main objectives include:

- To align with the Net Zero initiative
- To focus on key stages related to emissions
- Reducing greenhouse gas (GHG) emissions and improving energy efficiency
- Promoting Sustainability by supporting autonomous networking for secure and efficient industrial processes

4.1.2.2.2 Define the assessment depth

Tier assessments in ITU-T L.1480 provide flexibility, enabling users to choose a level of detail appropriate to their needs while ensuring that the methodology aligns with the standard. This tiered approach ensures both accessibility for entry-level assessments and robustness for advanced evaluations. Tier 1 assessments evaluate net second-order effects and assess contextual factors and higher-order effects using quantitative methods if robust, or qualitative methods otherwise. These are the most detailed assessments. Tier 2 assessments focus on net second-order effects and identify contextual factors and higher-order effects without quantifying the latter. These are of intermediate depth. Tier 3 assessments consider net second-order effects and identify contextual factors and higher-order effects qualitatively. These are the simplest and least rigorous assessments.

This step corresponds to the definition of the type of assessment. The intended assessment depth for this assessment is Tier 3 depth.

Table 15 shows the main characteristics of the defined assessment, in relation to a "Tier 3" requirement level as described in ITU-T L.1480 standard.

Table 15 Tier 3 Properties

Specification	Tier 3
Type	Screening / first approximation
Lifecycle stages	All (as material)
Data quality	Secondary (generic, proxies, averages)
ICT solution boundaries	Full life cycle
Reference scenario boundaries	Full life cycle
Data coverage and cut-off within boundaries	Proxy data used to cover data gaps.
Second-order effects, including induction	Cut-off rules apply.
Higher order effects	Should be identified
Long-term effect of any order	To be identified and reported. Considered in accordance with Tier 3 rules.
Adverse environmental and social effects	To be identified and reported. Considered in accordance with Tier3 rules.
Contextual factors	Should be identified

4.1.2.3 Step 2 – Scoping

This study evaluates the environmental impacts of ICT solutions, focusing on the definition of goal and scope as the foundational step in compliance with ITU-T L.1480. In defining the scope of an LCA, the following items are considered and clearly described in their respective document.

- the Reference scenario and the Green solution scenario to be studied;
- the impact order;
- the assessment depth;
- the consequence tree;
- geographical scope; the region covered in the analysis.
- temporal scope; the time frame for data collection and analysis.
- the functional unit;
- the system boundary;
- allocation procedures;
- LCIA methodology and types of impacts;

- data requirements;
- assumptions;
- limitations;
- data quality requirements;
- type of critical review, if any.

The goal and scope of the study may be revised due to unforeseen limitations, constraints or as a result of additional information. Such modifications, together with their justification, are documented.

4.1.2.3.1 Define the ICT solution and the main second-order effect

The type of evaluation is a specific ICT solution implemented in a specific context (i.e., a demonstrator presented as a pilot system). Commercial deployment was not taken into consideration.

4.1.2.3.1.1 Definition of the ICT solution

An Ethernet switch-based ICT solution is considered to define the Green ICT-enabled scenario and to compare it with the reference scenario. The main effect of the Green ICT-enabled scenario is to replace the traditional human inspection-based Quality Assurance process by introducing an automated Quality Assurance system, which can improve the industrial production processes (**Figure 20**). The system uses high-definition industrial cameras to capture pictures of the products on a conveyor belt and assess them for flaws and manufacturing defects. This visual inspection system optimizes energy use by reducing on-site manual computational resources. This shift also reduces physical infrastructure needs, lowering emissions from transportation and on-site operations. Here, the solution is a significant step forward compared to the human-based reference scenario, particularly in reducing energy use, lowering carbon emissions, and enabling higher efficiency.

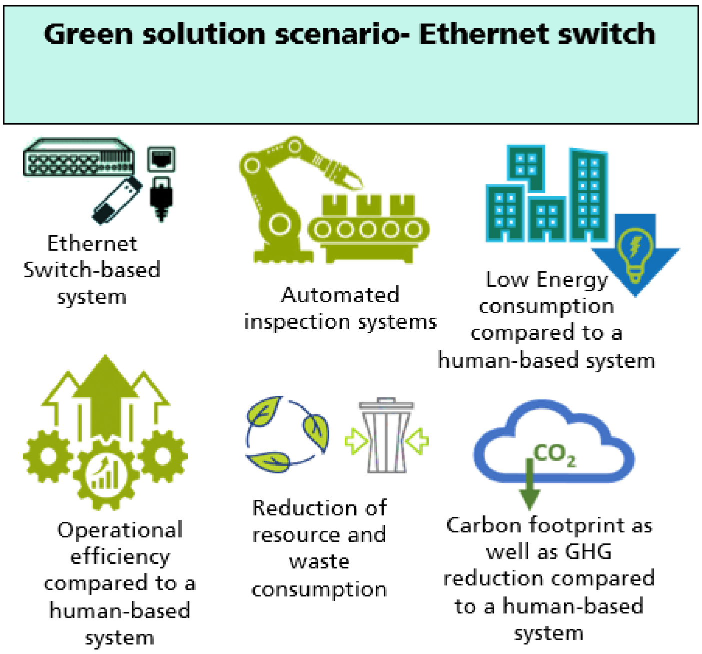


Figure 20: ICT solution scenarios (Ethernet switch-based); main GHG emission reduction-related effect for the introduction of the ICT solution

Here, the improvement pathway is the Ethernet switch-based solution where human inspection is replaced by automated inspection systems supported by electric switches, thus moving us away from manual, commute-dependent labour. This brings clear benefits a low energy consumption, a reduction in carbon footprint and greenhouse gases, less resource and waste consumption, and greater operational efficiency compared to the reference scenario.

In addition, the use of a robotic arm in combination with the dedicated Programmable Logic Controller (PLC) enables sorting the objects based on defect detection. The robotic arm is collocated with the conveyor belt. This system leads to less human intervention. The robotic arm sorts the manufactured artifacts, where faulty products are discarded, and non-faulty products are put onto the conveyor belt to continue into production. An automated visual inspection system for quality assurance decreases human error while providing consistent, high-quality defect detection. Reducing defective units and minimizing excess runs during production lowers overall energy and material use. This provides tangible GHG emissions reduction from decreased waste, energy use, and defective products.

4.1.2.3.1.2 Main expected second-order effect

The main expected second-order effect is to replace the Traditional human inspection-based Quality Assurance process by introducing an automated Quality Assurance process. The use of the ICT solution-based quality assurance reduces the need for manual inspection, which can lower energy consumption associated with human labour and emissions from commuting transportation, and reduce errors in production. The automation of quality assurance control leads to faster and more efficient production processes, reducing energy consumption per unit of output.

4.1.2.3.2 Define and describe the ICT solution under study

The ICT solution requires the following functions:

- Industrial cameras, which capture high-resolution video of items on a production line and ensure proper lighting and positioning for accurate fault detection.
- Computing system for the cameras for performing the video analysis and processing that analyses images of manufactured artefacts and looks for defects in real time.
- For an Ethernet switch-based solution, aggregation switches, core switch, optical module, and access switches are required to ensure smooth network communication.

4.1.2.3.3 Describe the main impact of the ICT solution on emissions in other sectors

This use of this ICT solution could reduce the GHG emissions of the conventional visual inspection system, by replacing human labour, introducing hardware such as robotic arms, and PLCs to increase the energy efficiency as well as the system efficiency in manufacturing industries.

4.1.2.3.4 Define the geographical and temporal coverage of the assessment

The components of the ICT solution are manufactured in China; the solutions aim to provide service for the development of smart industrial processes anywhere around the world.

As a result of the secondary data collection, the network system can extend for a 10-year service life, which is the average lifetime of a production line (Source: Statistics Canada, 2007), so the study will focus on these 10 years.

4.1.2.3.5 Clarify whether the quantification of the main second-order effect will be based on primary data

As the study is about a project (ex-ante situation), secondary data for all stages of the assessment were gathered. Secondary data has been gathered from interviews with potential users and literature sources to evaluate the main second-order effect scenario.

4.1.2.3.6 Defining the functional unit

The study under evaluation consists of 1000 VIS stations equipped with 2 devices (1 camera and 1 robotic arm), a realistic scale for large smart manufacturing environments. So, the functional unit is the average lifetime of a production line, which is 10 years (Statistics Canada, 2007) and 24/7 operational service of 1000 VIS stations, where yearly working days are 261 (EspoCRM, 2025), and working hours are 24 hours/day.

4.1.2.3.7 Defining the assessment perspective

The potential effect of the ICT solution under development is assessed.

4.1.2.3.8 Defining the composition of the ICT solution and identifying the contributors to its overall first order effects

Table 16: Identified First-order impacts

No.	Consequence	Description	I/D
1a1.	ICT components used for Ethernet switch solution, e.g., aggregation switch, access switch, optical modules, etc.	Emissions from networking equipment, considering their cradle-to-grave phase	I
1a2.	Visual inspection by industrial cameras	Emissions from camera manufacturing and energy consumption while performing the task, as well as possible EoL of the camera (cradle-to-grave)	I
1b1.	Servicing of the Ethernet switch solution	Maintenance operations/ Repair and replacement of ICT components	D

Note: I = Immediate, D = delayed

4.1.2.3.9 Identifying and defining the reference scenario

This reference scenario (**Figure 21**) presents traditional quality assurance processes in a manufacturing environment. It is less efficient and resource-intensive than the advanced network solutions. The reference scenario would include:

Human-Based Inspection

Quality assurance is performed by human workers who visually inspect products on the production line, and the number of required workers depends on the conveyor belt size and the intensity of incoming parts. This process is labour-intensive, time-consuming, and prone to human error, leading to inconsistencies in quality control. Human-based inspection may lead to a higher demand for physical infrastructure, increasing the carbon footprint from maintaining multiple inspection stations.

Higher transportation usage

For human inspection, there is an emission from the commuting of workers to the workplace. Depending on the distance, mode of transport, and number of workers, these mobility-related impacts can significantly increase the total carbon footprint of the inspection process. In high-labour environments, commuting emissions may represent a notable share of indirect impacts.

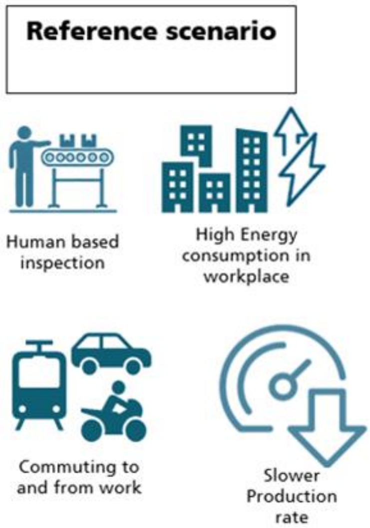


Figure 21: Visual presentation of reference scenario

High Energy Use

The energy usage of human labour also adds up to the overall energy usage at the workplace. In addition to machine and equipment consumption, the energy required to support human labour contributes to the overall energy footprint of the workplace. Activities such as lighting, heating, or cooling, and the operation of personal tools or devices increase the total energy demand associated with human-based operations.

Slower Production Process

Traditional inspection processes are slower and less accurate. Human-based inspection is inherently slower than automated vision systems due to manual handling, subjective judgment, and varying operator performance. Defects may go unnoticed, especially subtle or repetitive ones, resulting in defective items reaching later stages of production. And this may result in higher scrap rates and rework costs.

The reference/ baseline scenario in the visual inspection use case represents a traditional, inefficient, and resource-intensive approach to quality assurance. By transitioning to Ethernet switch-based solutions, manufacturers can achieve significant improvements in efficiency, scalability, and sustainability, while also addressing workforce and environmental challenges.

4.1.2.3.10 Identifying additional second and higher-order effects of using the ICT solution

As discussed before, the main expected second-order effect (generic Consequence 2a. "Introduction of Automated Quality Assurance") is to replace the traditional human inspection-based Quality Assurance process by introducing an automated Quality Assurance system.

Second-order impacts are the indirect environmental impacts resulting from the application of ICT solutions in non-ICT sectors, enabling them to operate more efficiently or sustainably. These impacts are often related to changes in behaviour, processes, or systems enabled by the technology. The second-order effects depict that the enhanced applications and efficiencies enabled by this solution can increase energy efficiency and reduce the carbon footprint that can result from:

- Automated quality assurance, which reduces resource consumption and enhances production efficiency
- Introducing advanced networks and robots to reduce human and physical infrastructure that decreases energy and resource consumption in the workplace, and travel to the workplace

4.1.2.3.11 Identification of second order effects of using the ICT solution

Table 17: Identification of second-order effects of using the ICT solution

No.	Consequence	Description	I/D
2a1a.	Evolution of time for performing the task / Improved work efficiency	The traditional and human-based inspection system is comparatively a slower process	I
2a1b.	Addition of emissions for robotic arms	Product footprint considering cradle-to-grave phase	I
2a1c.	Addition of dedicated hardware (e.g., PLCs)	Product footprint considering cradle-to-grave phase	I
2a1d.	Evolution of travel for reducing human labour	Reduced travel of human labour	I
2a2a.	Evolution of the energy consumption in the workplace building	Introducing advanced networks and robots to reduce human and physical infrastructure decreases energy consumption in the workplace	D
2a2b.	Evolution of the waste consumption in the workplace building	Introducing advanced networks and robots to reduce human and physical infrastructure decreases resource consumption in the workplace	D
2b1.	Evolution in the expected reduced human intervention for utilizing the same workforce in the same workplace	If the reduced workforce is utilized in other operations in the same workplace, then overall consumption can be increased.	D
2b2.	Evolution of the production of company vehicles	Changes in the production of company vehicles used by employees to travel to their usual place of work provided by the companies	D

Note: I = Immediate, D = delayed

4.1.2.3.12 Identification of higher-order effects

Table 18: Identification of higher-order effects

	Consequence	Description	I/D
3a1a.	Financial gains or losses by the Ethernet switch solution seller	The vendor of the connected solution generates operating income linked to its sales, whose gains or losses are used in other parts of its business activity	I
3a1b.	Financial gains or losses by the Ethernet switch solution user	The evolution in maintenance compared to the cost of implementing and managing the ICT system generates losses or gains for the user of the solution, which can be reused elsewhere	I
3b1.	Evolution of production volumes due to industry expansion	The adoption of smart factories may lead to increased production volumes, which may increase resource consumption as well as environmental impact unless managed sustainably.	D
3b2.	Development of ICT solutions for extra or improved purposes	Use of the smart ICT solution for further purposes (this could increase the data volume to be processed and transferred and production of more ICT components).	D
3b3.	New job markets	Improved connectivity may foster digital business models, thereby giving rise to new employment opportunities and strengthening industrial competitiveness.	D
4a.	Evolution of job displacement in certain sectors	(non-carbon effect)	D
4b.	Evolution of public popularity of smart cities and the Green ICT concept	(non-carbon effect)	D
4c.	Evolution of Digital Divide & Accessibility Issues	(non-carbon effect)	D

Note: I = Immediate, D = delayed

4.1.2.3.13 Identification of contextual factors

In general terms, contextual factors are the conditions or circumstances outside of which influence a system, process, or assessment. In the case of the Life Cycle Assessment (LCA) and the ITU-T L.1480, contextual factors are those expediting or impeding environmental impact assessment of ICT solutions; they could keep within the scope of the study, but are certainly not part of the said system. Contextual factors that can be potentially relevant for the assessment are as elaborated.

Economic Factors:

- While the capital investment in switch networks, cameras, and robotic arms is pretty huge. However, the long-term operational cost savings from automation and centralized control can always make up for the initial capital.
- Availability of subsidies or tax benefits connected with industrial automation.

Structural Factors:

- Capability of the industry to implement the infrastructure; power efficiency of cameras and sensors used for visual inspection.
- The accuracy and reliability of any automated visual inspection system, dependent on the quality of computation used for different types of defect detection.
- Type of production line and frequency of quality checks performed.

Regulatory and Standards Contextual Factors:

- Compliance with Industry Standards
- Data Privacy and Security

Human and Behavioural Factors:

- Such considerations are the willingness of industries to go from manual to automated quality control.
- The level of IT technical knowledge and support available for maintaining and troubleshooting the system.

4.1.2.3.14 Selection of effects to be quantified

Depending on the data availability, the quantifiable effects were selected.

4.1.2.3.14 Defining the system boundaries of the ICT solution scenario and the reference scenario

The identified effects and external factors are shown in the consequence tree below

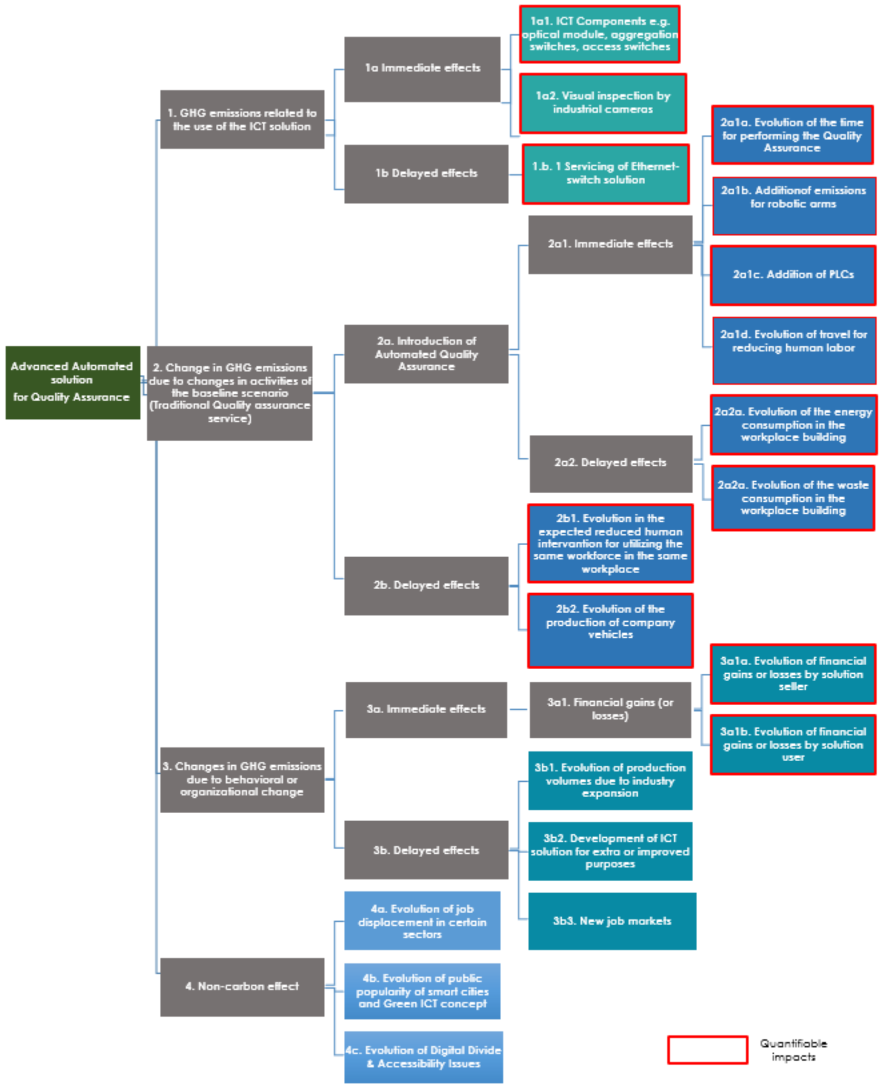


Figure 22: Consequence Tree developed for the study

4.1.2.4 Step 3 - Modelling, data collection and calculation

4.1.2.4.1 Data collection

4.1.2.4.1.1 Data collection for the reference scenario

To specify and quantify the reference scenario for an ex-ante study, information was collected primarily from literature references and also from the ICT vendor. For LCA modelling Ecoinvent 3.11 database was used.

The architecture of the Ethernet switch-based system was developed by the Fraunhofer HHI F5G openLab research team, considering smooth operation and redundancy. Data related to the following aspects were collected:

- Carbon footprint data for components of Ethernet switch-based solution, i.e., core switch, aggregation switch, access switch, and optical module
- Product datasheet of the components to assess use-phase consumption
- Carbon footprint data of physical PLCs
- Carbon footprint data of the industrial camera and robotic arm
- Percentage of the ICT components that need to be replaced during the lifetime

- Carbon footprint of human workers
- Average commuting distance and carbon footprint from workers' travel to the workplace
- Average workplace energy and waste consumption by human workers

4.1.2.4.1.2 Product Carbon Footprint – Ethernet switch-based solution

The required components for the Ethernet switch-based solution are listed as follows:

- **Core switch（24 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution, and end-of-life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for the use phase GHG estimation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase-10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Core switch	2,687	51.2	99,530	52.6	3,344

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **100GE QSFP28 optical module**

For raw material extraction, manufacturing, distribution and end-of-life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use-phase GHG estimation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase-10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Optical module	1.21	0.004	104.17	0.004	3.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Aggregation switch（24 x 10GE SFP+, 2 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase-10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Aggregation switch	163	1.3	7,559.96	0.5	254

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Aggregation switch（48 x 10GE SFP+, 4 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG assessment, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase-10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Aggregation switch	163	1.3	8,661.22	0.5	291

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **10GE SFP+/28 optical module**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase-10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Optical module	1.21	0.004	44.65	0.004	1.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)**

For raw material extraction, manufacturing, distribution, and end-of-life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor.

The maximum power consumption value from the data sheet of a product with the same configuration was used for the use-phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Robotic arm	39.55	0.28	5,357.5	0.075	180

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.2.4.1.3 Product Carbon Footprint – Industrial cameras

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Wazeem, 2022). The maximum power consumption value (i.e., 5.8 Wh) of the product (weight 100 g) of a similar configuration was used for use phase GHG calculation of the industrial camera. Collected data per product for GHG estimation for the functional unit is as follows:

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase (estimation of 10 years using industrial camera power consumption information from the product data sheet)	172.63
EoL	0.003775
Total	205.14

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.2.4.1.4 Product Carbon Footprint – Robotic Arms

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Wyatt et al., 2017). The maximum power consumption value (i.e., 180 Wh) of the product (weight 4 kg) of a similar configuration was used for use phase GHG calculation of the robotic arm. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Robotic arm	39.55	0.28	5,357.5	0.075	180

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.2.4.1.5 Product Carbon Footprint – Programmable Logic Controller (PLCs)

One PLC was considered for one VIS system. For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Source: Pérez-Martínez et al., 2021). For use-phase GHG estimation, power consumption data from the literature source were gathered. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Production & Distribution(Kg CO2e)	Use phase- 10 years (KgCO2e)	Transport for EoL(Kg CO2e)	EoL(Kg CO2e)
PLC	15.55	1,040.596	2.85	-9.48

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.2.4.1.6 Carbon Footprint Data related to Human workers

In one manufacturing line, automated optical inspection cut cycle time by 20% (Manual Vs. Automated Inspection: Striking the Right Balance for Quality and Throughput – NRM Mühendislik, 2025)

Therefore, Automated time= 0.8×Human time

So, Human time= 20.41/ 0.8= 25.5125 seconds

Then, one human takes 25.51 seconds per product.

From the F5G openLab data, it was estimated that a robotic arm takes 20.41 seconds per product. So in 10 years, QA of 11,048,700,000 products can be finished by 1000 robotic arms.

Now, total products for QA by robotic arms in 1000 VISs for QA in 10 years: 11,048,700,000

Time needed for Human workers for QA of the defined quantities of the product,

Total seconds per day: 24×3600=86,400 s/day

Products/day per worker: 86,400/ 25.51=3,387.68

products/year: 3,387.68×261=883,166 products/year per worker (Total working days 261)

Products per year for 1000 workers

883,166×1000=883,166,000 products/year

So, Years needed=11,048,700,000/ 883,166,000 =12.5 years

Hence, to do QA of 11,048,700,000 products by 1000 workers in 1000 VISs takes 12.5 years.

Therefore, the GHG emission assessment associated with human worker activities will be considered for 12.5 years.

The paper by Rugani et al. (2012) provides GHG emission factors per hour of human labour for three categories of workers, derived from environmentally extended input–output (EEIO) modelling based on household expenditure patterns. From the paper, carbon footprint data per worker per hour is 0.41 kg CO_2e/h.

For the estimation of GHG reduction from reducing travel of human workers, data from BBSR Statistics, (2023) shows that the average one-way commute is 17.2 km . So, the average travel per worker per day is 34.4 km. Statistisches Bundesamt (Destatis, 2025) points that, means of transport used by commuters for the workplace in Germany are 68% personal car, 13% public transport, 10% bycycle, 7% on foot, and 1% other.

Table 19: Average travelled distance and emissions per day per transportation type

Type of transport	Travelled distance (Km) (Statistisches Bundesamt, 2025)	GHG $KgCO_2e/km$ (Ecoinvent 3.11 database)
Personal car	23.392	0.242
Public transport	4.472	0.096 (The calculated average GHG emission of a bus per km is 0.125 kgCO2e, and train per km is 0.067 kgCO2e; the average of both the emissions, i.e., 0,096 kgCO2e, is used for public transport emission estimation
Bicycle	3.44	0.011
Electric scooter	0.344	0.06149

For the estimation of workplace energy consumption, data of the energy cost of both male and female workers in manufacturing industries was collected from a literature source (Poulianiti et al., 2019) and then the average energy consumption per worker per day was calculated.

Table 20: Energy cost in Manufacturing Sectors (kcal/min and Watts) (Poulianiti et al., 2019)

Manufacturing Sector	kcal/min (Male)	kcal/min (Female)	Watts (Male)	Watts (Female)
Food products, beverages & tobacco	3.020	2.030	210	142
Textiles & wearing apparel	2.903	1.743	202	122
Leather & related products	2.850	—	200	—
Wood & products of wood & cork	4.130	—	288	—
Paper & paper products	5.420	—	378	—
Printing & recorded media	2.90	—	202	—
Coke & refined petroleum	6.35	5.52	443	385
Chemicals & pharmaceutical products	4.86	—	339	—
Rubber & plastic products	3.92	—	273	—
Non-metallic mineral products	5.28	—	352	—
Basic metals	5.052	—	352	—
Fabricated metal products (excl. machinery)	3.05	3.12	175	250
Computer, electronic & optical products	3.65	—	255	—
Machinery & equipment	3.263	2.20	228	153
Motor vehicles, trailers & semi-trailers	3.367	2.82	235	197
Furniture	3.090	—	215	—
Other manufacturing	3.809	3.029	266	211
Repair & installation of machinery	4.900	—	342	—

For the estimation of workplace waste consumption, data of the waste type and amount in different types of industries were collected from a literature source (Sardan, 2019) and then the average waste consumption per worker per day was calculated in the result section.

Table 21: Daily non-hazardous industrial waste (NHIW) Generation per Worker in Industrial Sectors (Sardan, 2019)

Industrial Sector	No. of Workers	Total	Plastics	Paper	Cardboard	Wood	Metal	Glass	Others
Agricultural and Food	9,089	13.68	3.91	0.07	0.09	0.03	0.03	0.01	9.54
Chemical	7,449	22.58	8.72	0.12	0.09	0.02	11.98	0.00	1.65
IT, Engineering, and Electrical	8,083	4.09	0.07	0.01	0.02	0.02	1.05	0.11	2.82
Medical Equipment and Therapeutics	4,697	0.30	0.07	0.07	0.01	0.00	0.00	0.00	0.15
Packaging	5,403	4.74	2.03	0.92	0.81	0.00	0.17	0.00	0.80

4.1.2.4.2 Quantifying the first-order effects

Consequence 1.a.1: ICT components used for Ethernet switch solution, e.g., aggregation switch, access switch, optical modules etc.

The architecture of the Ethernet switch-based system was developed by the Fraunhofer HHI F5G openLab research team, considering smooth operation and redundancy. The listed components for the Ethernet switch solution are:

- Core switch (24 x 100GE QSFP28)
- 100GE QSFP28 Optical module
- Aggregation Switch (24 x 10GE SFP+, 1 x 100GE QSFP28)
- Aggregation Switch (48 x 10GE SFP+, 3 x 100GE QSFP28)
- 10GE SFP+/28 Optical module
- Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)

Product carbon footprint data was collected from the ICT vendor, who provided data for similar types of products per quantity (discussed in section 4.1.2.4.1). Use-phase data were collected from products of the same configuration used to develop the structure of the Ethernet switch-based solution by the F5G openLab research.

Table 22: GHG emission of Ethernet switch solution for 1000 VIS stations

Product requirements for 1000 VISs	Product Quantity	Raw material acquisition and Production	Distribution	Use	End of life	Total Kg CO_2e
Core switch (24 x 100GE QSFP28)	1	2,687	51.2	99,530	52.6	102,320
100GE QSFP28 Optical module	22	26.62	0.088	2,291.80	0.088	2,319
Aggregation Switch (24 x 10GE SFP+, 2 x 100GE QSFP28)	1	163	1.3	7,559.96	0.5	7,725
Aggregation Switch (48 x 10GE SFP+, 3 x 100GE QSFP28)	3	489	3.9	25,983.66	1.5	26,478
10GE SFP+/28 Optical module	336	406.56	1.344	15,000.8743	1.344	15,410
Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)	84	9,450	50.4	212,512.39	42	222,055
Total		13,222.18	108.232	362,878.293	98.032	376,306.74

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Therefore, the total GHG emission from the Ethernet switch-based ICT components was **376,306.74** Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Product requirements for 1000 VISs	Product Quantity	Raw material acquisition and Production	Distribution	Use (Energy source renewable energy)	End of life	Total Kg CO_2e
Core switch (24 x 100GE QSFP28)	1	2,687	51.2	21,249.61	52.6	24,040.41
100GE QSFP28 Optical module	22	26.62	0.088	489.30	0.088	516.096
Aggregation Switch (24 x 10GE SFP+, 2 x 100GE QSFP28)	1	163	1.3	1,614.055	0.5	1,778.85
Aggregation Switch (48 x 10GE SFP+, 3 x 100GE QSFP28)	3	489	3.9	5,547.52	1.5	6,041.92
10GE SFP+/28 Optical module	336	406.56	1.344	3,202.69	1.344	3,611.94
Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)	84	9,450	50.4	453,71.48	42	54,913.88
Total		13,222.18	108.232	77,474.66	98.032	90,903.10

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission from the Ethernet switch-based ICT components was **90,903.10** Kg CO_2e when renewable energy is used for the use phase.

Hence, shifting to renewable energy can save (376,306.74- 90,903.10) or 285,403.633 Kg CO_2e

GHG emissions, which is a **75.84%** savings (**Figure 23**).

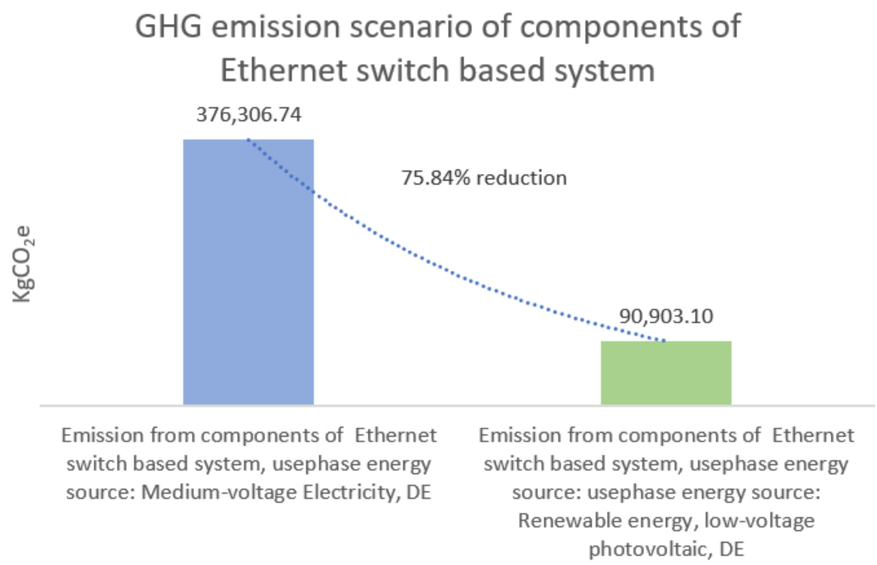


Figure 23: GHG emission from Ethernet switch solution

Consequence 1.a.2: Visual inspection by industrial cameras

As discussed in section 4.1.2.4.1.3 "Product Carbon Footprint- Industrial cameras", the collected data for one camera is as follows (Wazeem, 2022), Use phase data is from the F5G Open lab for the use case considering a 24/7 service and yearly working days 261.

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase from F5G Openlab data	172.63
EoL	0.003775
Total	205.14

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

So, for 1000 cameras, the total GHG emission is **205,143.098** Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase (Energy source renewable energy)	36.87
EoL	0.003775
Total	69.39

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 cameras is **69,386.63** Kg CO_2e when renewable energy is used for the use phase.

Hence, shifting to renewable energy can save (205,143.098 - 69386.63) or 135,756.46 kg CO_2e

GHG emissions, which is a **66.18%** savings (**Figure 24**).

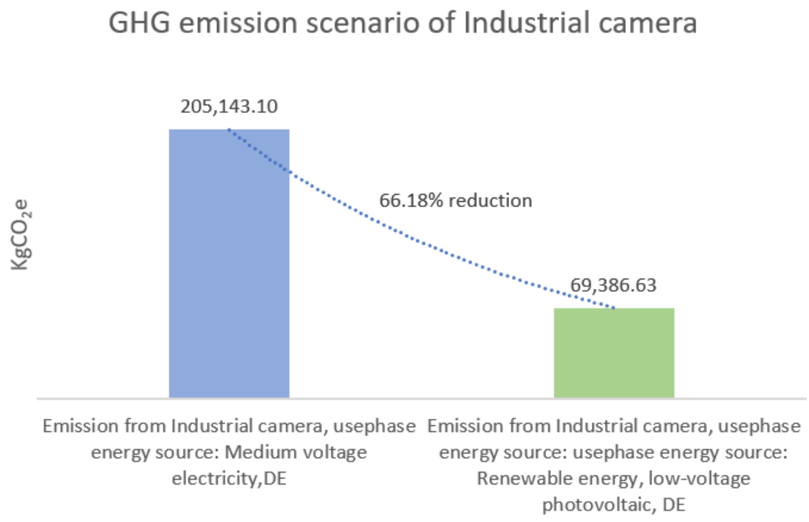


Figure 24: GHG emissions from Industrial cameras

Consequence 1.b: Maintenance/ Servicing of Ethernet-switch solution

It is a delayed impact. The calculation was done using proxy data to figure out the percentage of the Ethernet switches that need to be replaced during the lifetime of the components, and the data was gathered from an ICT vendor for ICT equipment.

For 10 years of the lifecycle of an ICT component, the proxy data shows a failure rate of <0.3% during that lifecycle.

Hence, for the core switch, GHG emission for maintenance: (0.3%* 102,320) or 306.96 $KgCO_2e$

For Aggregation switches, GHG emission for maintenance:

(0.3% * 7725) or 23.17 $KgCO_2e$ and (0.3% * 26,478) or 79.43 $KgCO_2e$

For Access switches, GHG emission for maintenance: (0.3% * 222,055) or 666.16 $kgCO_2e$

Therefore, the total estimated emission from maintenance of ICT components for 10 years of operational service is (306.96 + 23.17 + 79.43 + 666.16) or **1,075.73** $kgCO_2e$.

4.1.2.4.3 Quantify the second-order effects

Consequence 2.a.1.a: Evolution of time for performing the task / Improved work efficiency

In one manufacturing line, automated optical inspection cut cycle time by 20% ((Manual Vs. Automated Inspection: Striking the Right Balance for Quality and Throughput – NRM Mühendislik, 2025)

Therefore, Automated time= 0.8×Human time

From F5G openLab, it was estimated that a robotic arm takes 20.41 seconds per product.

So, Human time= 20.41/ 0.8= 25.5125 seconds

Then, one human takes 25.51 seconds per product.

Now, total products for QA by robotic arms in 1000 VISs for QA in 10 years: 11,048,700,000

For Human workers,

Total seconds per day: 24×3600=86,400 s/day

Products/day per worker: 86,400/ 25.51=3,387.68

products/year: 3,387.68×261=883,166 products/year per worker (Total working days 261)

Products per year for 1000 workers

883,166×1000=883,166,000 products/year

So, Years needed=11,048,700,000/ 883,166,000 =12.5 years

Therefore, the number of years that will be needed to inspect 11,048700,000 products by 1000 workers, where each worker takes 25.51 seconds per product: 12.51 years

Worker carbon footprint data: 0.41 kg CO_2e/hour/ worker (Rugani et al., 2012)

Total GHG of 1 worker for 12.5 years: =0.41*12.5*261*24 = 32103 kg CO_2e

Hence, for 1000 VISs and 1000 workers, the total GHG emission for the functional unit is **32,103,000** kg CO_2e.

Consequence 2.a.1.b: Addition of emissions for robotic arms

As discussed in section 4.1.2.4.1.4 "Product Carbon Footprint- Robotic Arms", product data for the Composite Double-Arm Type Robotic Arm was collected from a literature source (Wyatt et al., 2017). For the use phase, data is from the F5G Open lab for the use case considering a 24/7 service and yearly working days of 261.

	Manufacturing	Transportation	Use phase	End of Life	Total kgCO_2e
For 1 Robotic arm	39.55	0.28377	5,357.50	0.075	5,397.41
For 1000 robotic arms	39,547.16981	283.773	5,357,500.38	74.997	5,397,406.32

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Therefore, the total GHG emission for 1000 VISs is **5,397,406.32** Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase**.**

	Manufacturing	Transportation	Use phase (Energy source: renewable energy)	End of Life	Total kgCO_2e
For 1 Robotic arm	39.54717	0.283777	1,144.37	0.075	1,184.27
For 1000 robotic arms	39,547.171	283.777	1,144,368.73	74.997	1,184,274.67

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is **1,184,274.67** Kg CO_2e when renewable energy is used for the use phase.

Hence, shifting to renewable energy can save (5,397,406.32- 1,184,274.67) or 4,213,131.655 kg CO_2e GHG emissions, which is a **78.06%** savings (**Figure 25**).

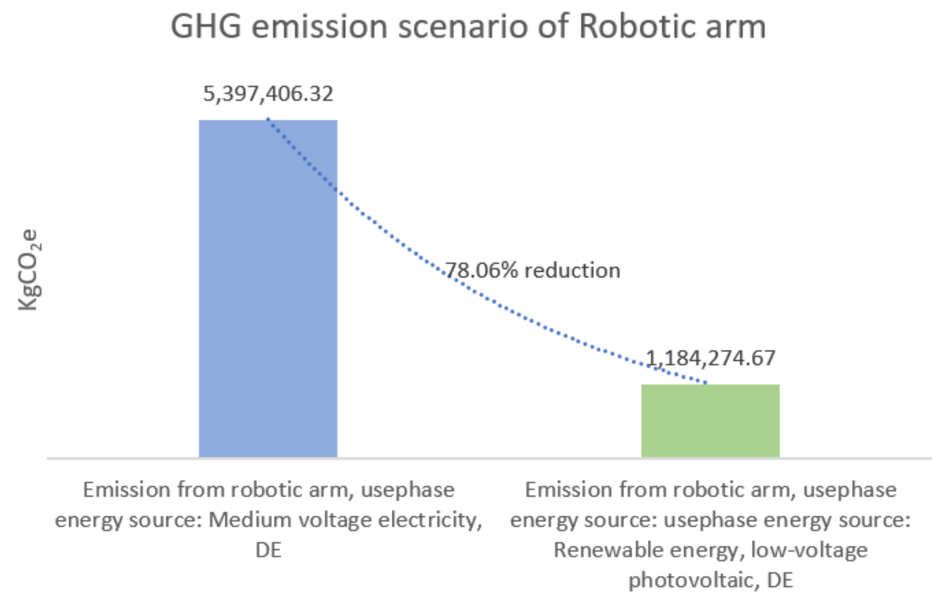


Figure 25: GHG emissions from Robotic arms

Consequence 2.a.1.C: Addition of dedicated hardware (e.g., PLCs)

As discussed in the data collection section 4.1.2.4.1.5 "Product Carbon Footprint- Programmable Logic Controller (PLCs)", product footprint and use phase data for the PLC were collected from a literature source (Pérez-Martínez et al., 2021). Use phase power consumption data was found in the source, it was modelled using the ecoinvent 3.11 database.

	Production & Distribution	Use phase	Transport for EoL	EoL	Total KgCO2e
PLC (1 item for 10 years of use phase)	15.55	1,040.596	2.85	-9.48	1,049.52
PLC (1000 items for 10 years of use phase)	15550	1,040,595.81	2850	-9480	1,049,515. 81

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Therefore, the total GHG emission for 1000 VISs is **1,049,515. 81** Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

	Production & Distribution	Use phase- renewable energy	Transport for EoL	EoL	Total KgCO2e
PLC (1 item for 10 years of use phase)	15.55	222.27256	2.85	-9.48	231.19256
PLC (1000 items for 10 years of use phase)	15550	222,272.56	2850	-9480	231,192.56

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is **231,192.56** Kg CO_2e when renewable energy is used for the use phase.

Hence, shifting to renewable energy can save (1049515. 81- 231,192.56) or 818323.25kg CO_2e

GHG emissions, which is a **77.97%** savings (**Figure 26**).

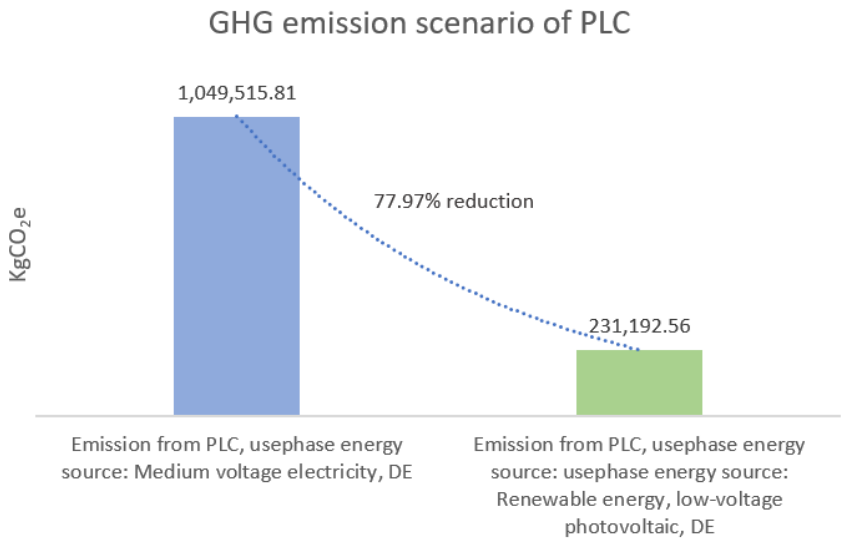


Figure 26: GHG emissions from PLCs

Consequence 2.a.1.d Evolution of travel for reducing human labourers

From the discussion in chapter 4.1.1.5.1.6, in Germany, the average one-way commute is 17.2 km (BBSR Statistics, 2023). So, the average travel per worker per day is 34.4 km. Statistisches Bundesamt (Destatis, 2025) shows that, means of transport used by commuters for the workplace in Germany are 68% personal car, 13% public transport, 10% bicycle, 7% on foot, and 1% other.

From the Ecoinvent 3.11 database, the calculated average GHG emission of a bus per km is 0.125 kgCO2e and train per km is 0.067 kgCO2e; the average of both the emissions, i.e., 0.096 kg CO_2e, is used for public transport emission estimation.

The average GHG emission of a personal car per km is 0.242 kg CO_2e.

The average GHG emission of a bicycle per km is 0.011 kgCO_2e.

The average GHG emission of an electric scooter per km is 0.06149 kgCO_2e, which is used for the calculation of other transport.

Table 23: GHG emission estimation from Travel

Type of transport	Travelled distance (Km)	$KgCO_2e$/km (Ecoinvent 3.11)	Total GHG $KgCO_2e$
Personal car	23.392	0.242	5.660864
Public transport	4.472	0.096	0.429312
Bicycle	3.44	0.011	0.03784
Electric scooter	0.344	0.06149	0.021

Therefore,

GHG from travel of one worker/day (5.660864+0.429312+0.03784+0.021)= 6.149$KgCO_2e$

GHG from travel of one worker/year (6.14916856*261) =1,604.93 $KgCO_2e$

GHG emission for 1000 workers for 12.5 years= (1604.93* 12.5)= **20,061,662.43** $KgCO_2e$

Consequence 2.a.2.a Evolution of the energy consumption in the workplace building

Energy consumption

Data from the literature source was collected (discussed in section 4.1.2.4.1.6 "Carbon Footprint Data related to Human workers") to estimate the average energy cost of workers in a manufacturing industry (Poulianiti et al., 2019). The estimated average energy cost is as follows

Table 24: Estimated average Energy cost per worker per hour

Worker Type	Energy cost-Watts (W)	Wh/hour
Male worker	278 W	278 Wh/hour
Female worker	204 W	204 Wh/hour
Average	258 W	258 Wh/hour

From **Table 24**, the average energy consumption per worker in the workplace is 258 Wh.

So, for 12.5 years, energy consumption per worker: 258*261*12.5*24= 20201,,400 Wh= 20,201.4 KWh.

For 12.5 years, GHG emission per worker (Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE): 9,598.773731$KgCO_2e$

Therefore, total GHG emission for 1000 workers: **9,598,773.731**$KgCO_2e$.

Again, the calculation was also done using renewable energy as an energy source for the use phase (LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE),

For 12.5 years, estimated GHG emission per worker: 2,050.32730 $KgCO_2e$, when renewable energy is used in operational phase.

Therefore, total GHG emission for 1000 workers is **2,050,327.30** $KgCO_2e$; which is 78.64% emission reduction from shifting to renewable energy (**Figure 27**).

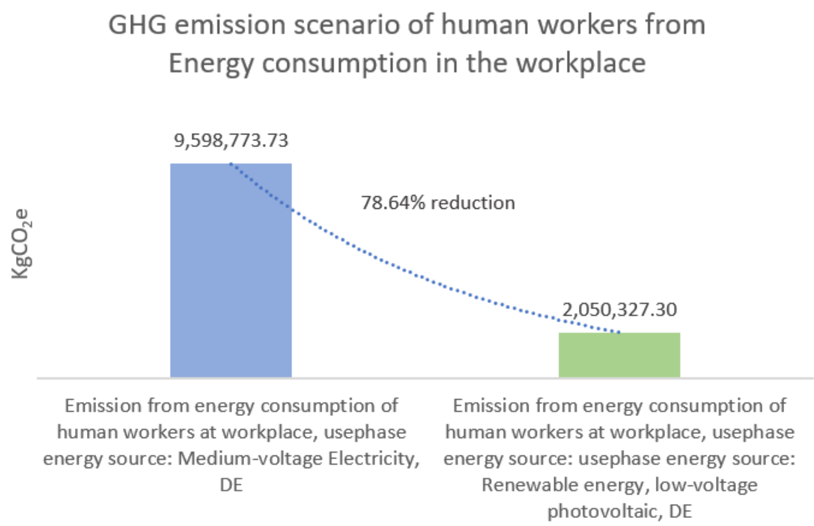


Figure 27: GHG emissions from the energy consumption of human workers

Consequence 2.a.2.b. Evolution of the waste consumption in the workplace building

Data from the literature source was collected (discussed in section 4.1.2.4.1.6) to estimate the average non-hazardous industrial waste (NHIW) consumption of workers in an industry (Saidan, 2019). The estimated average waste consumption per worker per day is as follows

Table 25 Waste type and amount per worker per day

Waste Type	Waste amount in Kg (per worker per day)	GHG per Kg waste (Data from Ecoinvent 3.11)	Estimated GHG ($KgCO_2e$) for the listed amount
Plastic	3.24	2.37543	7.6963932
Paper+ cardboard	0.38	0.01036	0.00394
Wood	0.02	0.02631	0.0005262
Glass	0.03	0.03819	0.0011457
Metal	2.85	0.0418	0.11913
Others	3.65	0.66456	2.425644

From the table, the GHG emission per worker per day: (7.6963932++0.00394+0.0005262+0.0011457+0.11913+2.425644) = 10.25 KgCO2e

Therefore, the GHG emissions of 1000 workers for 12.5 years = (10.25*261*12.5*1000)

= **26,744,093.45** KgCO2e.

Consequence 2.b.1: Evolution in the expected reduced human intervention for utilizing the same workforce in the same workplace

It is a delayed effect and will be estimated in the next release of the report.

Consequence 2.b.2: Evolution of the production of company vehicles

It is a delayed effect and will be estimated in the next release of the report.

4.1.2.4.4 Assessment of higher order effects including quantification

In this ex-ante study, higher-order impacts were identified in section 4.1.2.3.12 "Identification of higher-order effects" and will be estimated in the next release of the report.

4.1.2.4.5 Results presentation and analysis

4.1.2.4.6 Results

Table 26: Assessment Results

Consequences (Human-based vs Ethernet switch-based)	GHG Value	%	% per order
1a1. ICT components used for Ethernet solution, e.g., aggregation switch, access switch, etc. (I)	37,6306.74	0.39%	0.601%
1a2. Visual inspection by industrial cameras (I)	205143.098	0.215%	
1b1. Maintenance/ Servicing of Ethernet solution (D)	1075.73	0.0011%	
2a1a. Evolution of time for performing the task / Improved work efficiency (I)	-32,103,000	33.60%	99.399%
2a1b. Addition of emissions for robotic arms (I)	-5,397,406.324	5.65%	
2a1c. Addition of dedicated hardware (e.g., PLCs) (I)	-1,049,515.81	1.099%	
2a1d. Evolution of travel for reducing human labor (I)	-20,061,662.43	21.00%	
2a2a. Evolution of the energy consumption in the workplace building (D)- Energy	-9,598,773.731	10.05%	
2a2b. Evolution of the waste consumption in the workplace building (D)- Waste	-26,744,093.45	28%	
2b1. Evolution in the expected reduced human intervention for utilizing the same workforce in the same workplace (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
2b2. Evolution of the production of company vehicles (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
3a1a. Evolution of financial gains or losses by the solution seller and user (I) 3b1. Evolution of production volumes due to industry expansion (D) 3b2. Development of ICT solution for extra or improved purposes (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
Total (kgCO2e)	−94,371,926.18		
Total absolute value	95,536,977.31		

Note: I = Immediate, D = delayed

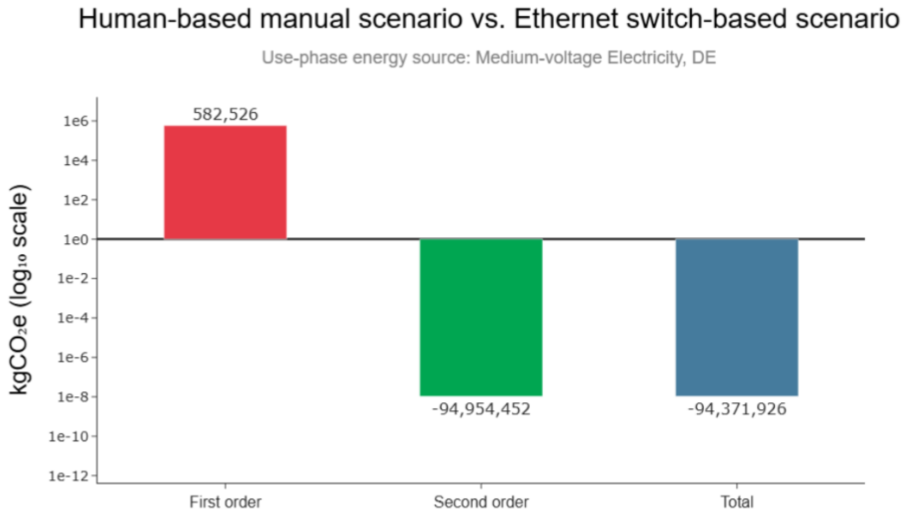


Figure 28: GHG emissions over 10 years

In addition, the table below shows the GHG emission scenario when renewable energy is used in the use phase, where applicable.

Consequences (Human-based vs Ethernet switch-based)	GHG Value	%	% per order
1a1. ICT components used for Ethernet solution, e.g., aggregation switch, access switch, optical module etc. (I)	90,903.10	0.110%	0.1953%
1a2. Visual inspection by industrial cameras (I)	69,386.63	0.084%	
1b1. Maintenance/ Servicing of Ethernet solution (D)	1075.73	0.0013%	
2a1a. Evolution of time for performing the task / Improved work efficiency (I)	-32,103,000	38.90%	99.8047%
2a1b. Addition of emissions for robotic arms (I)	-1,184,274.67	1.435%	
2a1c. Addition of dedicated hardware (e.g., PLCs) (I)	-231,192.56	0.28%	
2a1d. Evolution of travel for reducing human labor (I)	-20,061,662.43	24.31%	
2a2a. Evolution of the energy consumption in the workplace building (D)- Energy	-2,050,327.30	2.484%	
2a2b. Evolution of the waste consumption in the workplace building (D)- Waste	-26,744,093.45	32.40%	
2b1. Evolution in the expected reduced human intervention for utilizing the same workforce in the same workplace (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
2b2. Evolution of the production of company vehicles (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
3a1a. Evolution of financial gains or losses by the solution seller and user (I) 3b1. Evolution of production volumes due to industry expansion (D) 3b2. Development of ICT solution for extra or improved purposes (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
Total (kgCO2e)	−82,213,184.95		
Total absolute value	82,535,915.87		

Note: I = Immediate, D = delayed

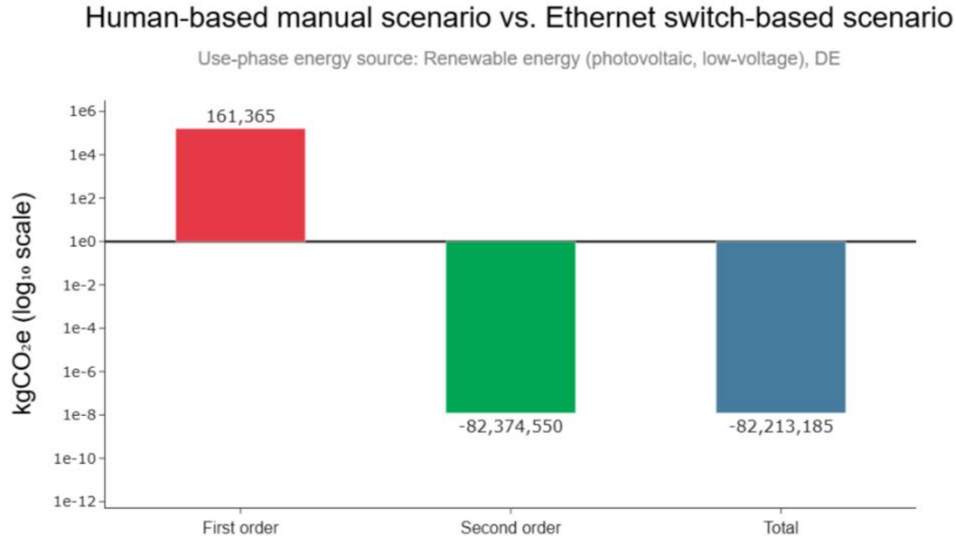


Figure 29: GHG emissions over 10 years, when renewable energy is used during the operational phase

4.1.2.4.7 Analysis of results

4.1.2.4.7.1 Disclaimer

The present study is conducted at a "Tier3" level of precision, particularly in view of its "ex-ante" nature, which requires us to imagine future usage and user behavior.

Under these conditions, it should be remembered that, about the scope and quality of the assessment obtained, Recommendation L.1480 states that the Tier 3 assessments "are the simplest assessments and are not considered rigorous" (§.10.1.2), provide a « screening / first approximation » (§.10.1.2 table 2) which "can only give initial guidance on the effect of ICT solutions" (§.13.3.2 and §.10.5 on reporting), thus "shall not be used for public or consumer communication" (§.13.3.2) and "should not be used as a sole input for [decision-making]" (Note on §.10.5).

With regard to the assessment process, "the establishment of the consequence tree [is] … recommended for Tier 3 assessments » (§.10.2), and "Tier 3 assessments should include all the effects in a consequence tree before any limitation or cut-off associated with the depth of the assessment and the chosen functional unit is performed" (§. 10.2.6), finally "Tier 3 assessments should consider net second order effects and should identify contextual factors and higher order effects. These are the simplest assessments and are not considered rigorous" (§.10.1.2).

4.1.2.4.7.2 Contribution to decarbonization

Subject to the above reservations Recommendation L.1480, Section 5.5.2.1 "Disclaimer", the use from 2025 of the ICT solution for automated visual inspection systems to reduce its carbon footprint by reducing GHG emissions by replacing manual visual inspection systems.

- emissions reduction of 94,371.93 TCO_2e over the 10-year operational lifetime of the VISs,
- emissions reduction of 82,213.18 TCO_2e over the 10-year operational lifetime of the VISs when renewable energy is used during the operational phase.

4.1.2.4.7.3 Importance of standards and certification

However, these improvements can only be realized if the measurement data generated by the system is proven to be sufficiently reliable to meet certification and compliance requirements. This also depends on relevant standards and regulations being updated to accept such measurement methods, and on the system successfully achieving formal certification. Only then can automated measurement processes legitimately replace conventional inspections.

Therefore, the essential first step within the quality assurance framework is to obtain certification for the proposed solution, ensuring it can be integrated into manufacturing operations while maintaining product quality and reducing operational impacts, including emissions.

4.1.2.4.7.4 Proportion of different effect classes

Here, the proportion in the balance on GHG emissions would be 0.601% due to the ICT solution itself (first-order effect) and 99.39% (second-order effect). Higher order impact proportion will be added in the next release of the report.

When renewable energy is considered, the proportion in the balance on GHG emissions would be 0.195% due to the ICT solution itself (first-order effect) and 99.80% (second-order effect). Higher order impact proportion will be added in the next release of the report.

4.1.2.4.8 Scaling up

The present study assumes 1000 VIS stations in the context of a large manufacturing industry, where one worker works per VIS station, and one robotic arm replaces one worker in the ICT use case scenario. Scaling up will be added in the next release of the report.

4.1.2.5 Step 4 - Interpretation of results

4.1.2.5.1 Evaluation of the applied method

The Tier3 level of precision described in Recommendation L.1480 has been applied, as is natural for an *ex-ante* evaluation in which, by definition, the uses of the ICT solution are not known with any precision, and even more so in the case of a new solution which is not active with any customer/user of the type studied.

4.1.2.5.2 Data quality analysis

Data relating to the use case has been obtained from literature sources and interviews with the ICT vendor. They can be considered sufficient and reliable for the desired Tier3 level of analysis.

Generic data were obtained from various sources and available literature.

4.1.2.5.3 Sensitivity analysis

The result depends entirely on the existence of standardization that recognizes the possibility of using data received from the ICT solution equipment to reduce GHG emissions of the quality assurance process in manufacturing industries.

The results of the visual-inspection use case are sensitive to several assumptions that affect both first-order and second-order GHG impacts. The most critical parameter is whether digital inspection data generated by the ICT equipment is recognized by manufacturing-industry standards and QA protocols as an acceptable basis for product certification. If such acceptance is not in place, manual inspection activities must continue, thereby reducing the emission-reduction potential.

Additional sensitivity factors include the power consumption of cameras, and network infrastructure, the number of manual inspection tasks replaced, worker travel distances, ICT-device lifetime, and the accuracy of defect detection. Adjusting these parameters within plausible ranges demonstrates that the overall GHG reduction potential may vary significantly, especially when inspection accuracy or ICT electricity consumption changes. Therefore, standardization, data-acceptance policies, and operational parameters of the ICT system play a decisive role in determining the robustness of the final GHG-impact outcome.

4.1.2.5.4 Uncertainty analysis

The GHG-emission comparison between an Ethernet-based automated visual inspection system and a conventional human-based inspection system is subject to several sources of uncertainty. Major uncertainties arise from the variability in ICT equipment energy consumption, differences between manufacturer specifications and real-world operation, and assumptions about the number of workers replaced by automation. The baseline human-activity data, including walking distances, time spent on inspections, and intralogistics support, also introduces substantial uncertainty due to dependence on observational estimates and production variability.

Further uncertainty can stem from inspection accuracy, duty-cycle assumptions, and the carbon intensity of electricity used by the Ethernet switch system. Equipment lifetime and system boundaries related to shared network infrastructure also influence the results. These uncertainties collectively affect both first-order and second-order impacts, indicating that real-world measurements, standardized QA procedures, and continuous data logging would significantly reduce the uncertainty of the final GHG-impact results.

4.1.2.6 Step 5 - Reporting

The study is reported aligning with the ITU-T L.1480 reporting format.

4.1.2.7 Step 6 - Critical review

Critical review ensures compliance with methodological requirements and increase the credibility and reliability of the LCA results. The main purpose is to conduct an impartial evaluation of the LCA study in compliance with ITU-T L.1480 standards to assure consistency between a life cycle assessment and the concepts and criteria of the International Standards on life cycle assessment. According to ITU -T L. 1480 recommendation, depending on the aim of the assessment, critical review may be recommended or required. It also states that if compliance with this Recommendation is claimed, practitioners are encouraged to share the report with the ITU-T SG5 Secretariat (tsbsg5@itu.int) for reference.

Besides, if the study aims to support a comparison claim for public disclosure, interested parties need to perform this evaluation as a critical review. The scope includes a concise overview of the LCA study, detailing the ICT system, functional unit, and system boundaries under consideration.

The internal review of the document has been conducted while implementing the assessment. This document has also been reviewed by AIOTI WG GIE.

4.1.2.8 References for use case “Visual inspection for automated Product Quality assessment”

EspoCRM. (2025, March 13). How many work days in a year? (2025) Updated. https://www.espocrm.com/blog/how-many-work-days-in-a-year/

Pérez-Martínez, M. M., Carrillo, C., Rodeiro-Iglesias, J., Soto-Benéitez, B., Dominguez, A., Vilela, I., & Lavín, A. G. (2021). *Life cycle assessment of repurposed waste electrical and electronic equipment: A case study*. *Sustainable Production and Consumption, 27*, 1637–1649. https://doi.org/10.1016/j.spc.2021.03.017

Poulianiti, K. P., Havenith, G., & Flouris, A. D. (2018). *Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries*. Journal of Physiological Anthropology, 37(1), 1–11. https://www.jstage.jst.go.jp/article/indhealth/57/3/57_2018-0075/_pdf/-char/ja

Reichel, J. (2023, October 25). *BBSR statistics: Germans are commuting more again – and over greater distances*. VISION mobility. https://www.vision-mobility.de/en/news/bbsr-statistics-germans-are-commuting-more-again-and-over-greater-distances-286007.html

Rugani, B., Panasiuk, D., & Benetto, E. (2012). An input–output based framework to evaluate human labour in life cycle assessment. *The International Journal of Life Cycle Assessment*, *17*(6), 795–812. https://doi.org/10.1007/s11367-012-0403-1

Saidan, M. N. (2019). Cross-sectional survey of non-hazardous waste composition and quantities in industrial sector and potential recycling in Jordan. *Environmental Nanotechnology Monitoring & Management*, *12*, 100227. https://doi.org/10.1016/j.enmm.2019.100227

Statistisches Bundesamt (Destatis). (2025). *Means of transport used by commuters, 2020* [Infographic]. https://www.destatis.de/EN/Press/2021/09/PE21_N054_13.html

Statistics Canada. (2007). *A portrait of seniors in Canada: Highlights from the 2006 Census* (Catalogue No. 11-402-X). https://www150.statcan.gc.ca/n1/pub/11-402-x/2007/4005/ceb4005_002-eng.htm

Wazeem, A. (2022). Life cycle assessment of a camera system: A case study (Master’s thesis, [University name]). DiVA – Digitala Vetenskapliga Arkivet. https://www.diva-portal.org/smash/get/diva2:1736686/FULLTEXT01.pdf

Wyatt, H., Wu, A., Thomas, R., & Yang, Y. (2017). *Life cycle analysis of double-arm type robotic tools for LCD panel handling*. Machines, 5(1), 8. https://doi.org/10.3390/machines5010008

4.1.3 GHG impact assessment of "Edge-cloud based visual inspection for automated Product Quality assessment" use case

Since September 2022, the Fraunhofer HHI Institute has started developing a solution to improve the industrial production processes with an AI-powered Passive optical network (PON)- based automated industrial visual inspection system. Automating visual inspection for quality assurance in operational processes can enhance quality control of produced artefacts, boost production volumes, and minimize human resource engagement in repetitive tasks. The study aims to evaluate, at a Tier 3 level of precision, the extent to which an automated cloud-based quality assurance system can diminish greenhouse gas emissions for its users. This example follows the L.1480 approach as stated in its steps, shown in Figure 1 ("Assessment Procedure Overview") of ITU-T Recommendation L.1480 [ITU-T L.1480].

This section provides a GHG impact assessment of the Edge-cloud based visual inspection for the automated Product Quality assessment use case, using the revised ITU-T L.1480 recommendation.

A brief overview of this use case is provided in Section 3.1.2 of this report, and depicted in Figure 5 (b) – the PON based solution.

4.1.3.1 Introduction

This supplement illustrates the implementation of the main steps of the assessment methodology described in ITU-T Recommendation L.1480 [ITU-T L.1480]. It presents a "Tier 3" evaluation relating to an *ex-ante* case study of a project of Edge-cloud based visual inspection for an automated Product Quality assessment study case.

4.1.3.2 Step 1 - Define the goal of the assessment

4.1.3.2.1 Define the aim and type of the assessment

F5G OpenLab, an open research laboratory aimed at fostering fiber-based solutions for industrial digital transformation. The lab provides a vendor-neutral platform for testing and validating next-generation networking solutions, with a focus on enabling the twin transitions (digital and green transformation). It aims to create a sustainable and eco-friendly ICT industry by fostering the development of secure and trustworthy autonomous networking solutions. The purpose of the case study is to evaluate the GHG emissions linked to the deployment of an advanced passive optical network (PON)-based ICT solution located at Fraunhofer HHI in Berlin, Germany.

Main objectives include:

- To align with the Net Zero initiative
- To focus on key stages related to emission
- Reducing Green House Gas (GHG) emissions, and improving energy efficiency
- Promoting Sustainability by supporting autonomous networking for secure and efficient industrial processes

4.1.3.2.2. Define the assessment depth

Tier assessments in ITU-T L.1480 provide flexibility, enabling users to choose a level of detail appropriate to their needs while ensuring that the methodology aligns with the standard. This tiered approach ensures both accessibility for entry-level assessments and robustness for advanced evaluations. Tier 1 assessments evaluate net second-order effects and assess contextual factors and higher-order effects using quantitative methods if robust, or qualitative methods otherwise.

These are the most detailed assessments. Tier 2 assessments focus on net second-order effects and identify contextual factors and higher-order effects without quantifying the latter. These are of intermediate depth.

Tier 3 assessments consider net second-order effects and identify contextual factors and higher-order effects qualitatively. These are the simplest and least rigorous assessments.

This step corresponds to the definition of the type of assessment. The intended assessment depth for this assessment is Tier 3 depth.

Table 27 shows the main characteristics of the defined assessment, in relation to a "Tier 3" requirement level as described in ITU-T L.1480 standard.

Table 27:Tier 3 Properties

Specification	Tier 3
Type	Screening / first approximation
Lifecycle stages	All (as material)
Data quality	Secondary (generic, proxies, averages)
ICT solution boundaries	Full life cycle
Reference scenario boundaries	Full life cycle
Data coverage and cut-off within boundaries	Proxy data used to cover data gaps.
Second-order effects, including induction	Cut-off rules apply.
Higher order effects	Should be identified
Long-term effect of any order	To be identified and reported. Considered in accordance with Tier 3 rules.
Adverse environmental and social effects	To be identified and reported. Considered in accordance with Tier3 rules.
Contextual factors	Should be identified

4.1.3.3. Step 2 – Scoping

This study evaluates the environmental impacts of ICT solutions, focusing on the definition of goal and scope as the foundational step in compliance with ITU-T L.1480. In defining the scope of an LCA, the following items are considered and clearly described in their respective document.

- the Reference scenario and the Green solution scenario to be studied;
- the impact order;
- the assessment depth;
- the consequence tree;
- geographical scope; the region covered in the analysis.
- temporal scope; the time frame for data collection and analysis.
- the functional unit;
- the system boundary;
- allocation procedures;
- LCIA methodology and types of impacts;
- data requirements;
- assumptions;
- limitations;
- data quality requirements;
- type of critical review, if any.

The goal and scope of the study may be revised due to unforeseen limitations, constraints or as a result of additional information. Such modifications, together with their justification, are documented.

4.1.3.3.1 Define the ICT solution and the main second-order effect

The type of evaluation is a specific ICT solution implemented in a specific context (i.e. a demonstrator presented as a pilot system). Commercial deployment was not taken into consideration.

4.1.3.3.2 Definition of the ICT solution

Passive optical network (PON)-based ICT solution is considered to define the Green ICT-enabled scenario and to compare with the reference scenario. The main effect of the Green ICT-enabled scenario is to replace the Ethernet switch-based Quality Assurance process by introducing an edge cloud computing-based automated Quality Assurance system, which can improve the industrial production processes (**Figure 30**). The system uses high-definition industrial cameras to capture pictures of the products on a conveyor belt, uses artificial intelligence (AI) to assess them for flaws and manufacturing defects. This edge cloud-based visual inspection system optimizes energy use by reducing on-site computational resources. This shift also reduces physical infrastructure needs, lowering emissions from on-site operations. Here, passive optical solutions are significant steps forward compared to the Ethernet switch-based reference scenario, particularly in reducing energy use, lowering carbon emissions, and enabling higher efficiency.

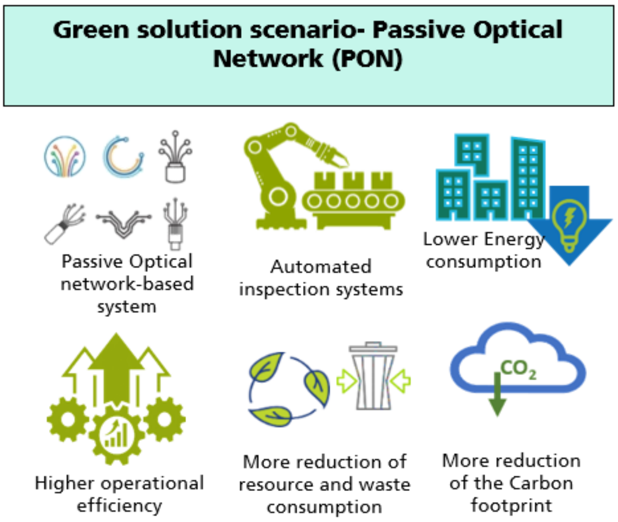


Figure 30: ICT solution scenario (PON based); main GHG emission reduction related effect for the introduction of ICT solution

Here, the improvement pathway is the PON-based solution. By shifting to fiber-optic networks, more gains can be achieved. It integrates fiber-to-the-camera and fiber-to-the-robot via a Passive Optical Network (PON) system consisting of an Optical Line Terminal (OLT) and Optical Network Units (ONUs). The Visual Inspection Station (VIS) interfaces with the edge/cloud using ONUs. Each ONU supports one camera or a robotic arm within the VIS, where a camera provides visual observation, an edge/cloud platform performs the analysis, and a robotic arm executes the physical action. The end-to-end observe-analyze-act (OAA) procedure provides an end-to-end video processing pipeline with remote computational capabilities.

Replacing traditional Ethernet switch-based systems enhances energy efficiency due to the lower power consumption of optical components, while simultaneously improving data processing and reducing hardware-dependent tasks. As a result, fiber networks enable the most efficient data transmission, lowering energy use and reducing the carbon footprint of industrial operations.

Moreover, in this solution, the use of a robotic arm in combination with the virtual Programmable Logic Controller (vPLC) that runs on the edge cloud sorts the objects based on the feedback of AI-based defect detection and operates using the control signals received from the edge cloud.

The robotic arm is collocated with the conveyor belt. This system leads to less human intervention. The robotic arm sorts the manufactured artefacts, where faulty products are discarded, and non-faulty products are put onto the conveyor belt to continue into production.

4.1.3.3.2.1 Main expected second-order effect

The main expected second-order effect is to replace the Ethernet switch-based Quality Assurance process by introducing a PON-based automated Quality Assurance process. The use of the edge cloud and PON ICT solution-based quality assurance reduces the quantity of hardware, which can lower energy consumption associated with the use phase and emissions from product manufacturing and end-of-life management. So, replacing traditional electric switches with passive optical network systems enhances energy efficiency by improving data processing and reducing hardware dependence. Fiber networks enable efficient data transmission, lowering energy use and reducing the carbon footprint of industrial operations.

4.1.3.3.3 Define and describe the ICT solution under study

In this use case scenario, as illustrated in **Figure 31**, the industrial camera captures images of products on the production line. Captured images are sent to the edge cloud for AI-based analysis. AI classifies objects as faulty or non-faulty based on predefined criteria, using pre-trained Machine Learning (ML) algorithms. The robotic control system receives sorting commands using the vPLC running on the edge cloud.

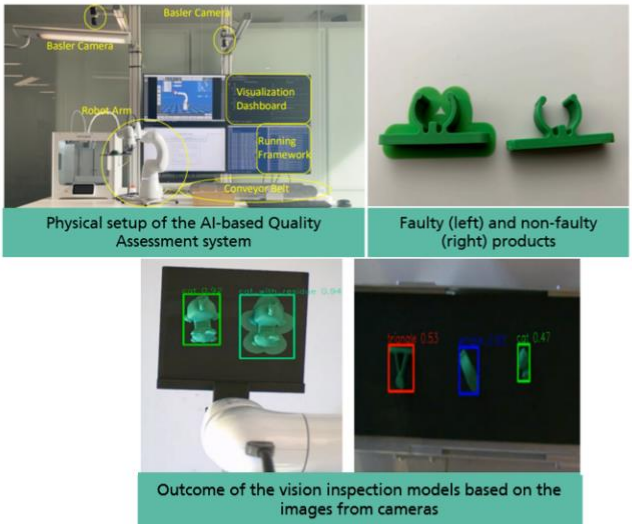


Figure 31: ICT solution use case scenario; Source: AIOTI, 2024.

Hence, this end-to-end ICT solution requires the following functions:

Industrial cameras that capture high-resolution video of items on a production line and ensure proper lighting and positioning for accurate fault detection.

Edge cloud data center, which is responsible for video analysis and processing, and for the telemetry framework and machine learning pipeline operation.

Edge-Cloud AI Processing that analyses images of manufactured artefacts and looks for defects in real time.

A control System (i.e., vPLC) of the robotic arm is used to support the operation of the robot arm and the communication of the control signals received from the edge-cloud. This system runs on the third server.

For an optical-based solution, PON components which interconnect all the components to ensure high-speed, low-latency communication between the operation floor and the edge-cloud.

4.1.3.3.4 Describe the main impact of the ICT solution on emissions in other sectors

This use of this ICT solution could reduce the GHG emissions of the conventional visual inspection system, by increasing the energy efficiency as well as the system efficiency in manufacturing industries.

4.1.3.3.5 Define the geographical and temporal coverage of the assessment

The components of the ICT solution are manufactured in China; the solutions aim to provide service for the development of smart industrial processes anywhere around the world. Data related to the assessment of this ex-ante study use phase was gathered from Germany.

As a result of the secondary data collection, the edge cloud-based optical fiber network system can extend for a 10-year service life, which is the average lifetime of a production line (Source: Statistics Canada, 2007), so the study will focus on this 10-year period.

4.1.3.3.6 Clarify whether the quantification of the main second-order effect will be based on primary data

As the study is about a project (ex-ante situation), primary data for all stages of the assessment could not be gathered. Primary data was used to calculate the PON components of the system for quantifying the first-order effect.

Secondary data has been gathered from interviews with potential users and literature sources to evaluate the main second-order effect scenario.

4.1.3.3.7 Defining the functional unit

The study under evaluation consists of 1000 VIS stations equipped with 2 devices (1 camera and 1 robotic arm), a realistic scale for large smart manufacturing environments. So the functional unit is the average lifetime of a production line, which is 10 years (Statistics Canada, 2007) and 24/7 operational service of 1000 VIS stations, where yearly working days are 261 (EspoCRM, 2025) and working hours are 24 hours/day.

4.1.3.3.8 Defining the assessment perspective

The potential effect of the ICT solution under development is assessed.

4.1.3.3.9 Defining the composition of the ICT solution and identifying the contributors to its overall first order effects

Table 28:Identification of first-order effects (Ethernet switch vs PON)

No.	No.	Consequence	Description	I/D
1a1. Difference between Ethernet switch and PON Scenario- Components	1a1a.	ICT components used for the ICT solution, e.g., OLT, ONUs, etc.	Emission from networking equipment considering their cradle-to-grave phase	I
	1a1b.	Emissions from components used for Ethernet solution		I
1a2. Emissions from vPLC- the Optical solution (Data center server)			Resource consumption during the operational phase	I
1a3. Difference between emissions from industrial cameras	1a3a.	Emission from cameras when PON solution is used	Emission from industrial cameras for VIS station, considering their cradle-to-grave phase	I
	1a3b.	Emission from cameras when Ethernet switch solution is used		I
1b1. Difference between Ethernet switch and PON Scenario- Servicing/ repair and replacement	1b1a.	Servicing of the Optical solution	Maintenance operations/ Repair and replacement of ICT components	D
	1b1b.	Servicing of Ethernet solution		D

Note: I = Immediate, D = delayed

4.1.3.3.10 Identifying and defining the reference scenario

This reference scenario presents Ethernet/ electrical switch-based quality assurance processes in a manufacturing environment. It is less efficient and resource-intensive than the advanced fiber-based and edge cloud solutions. The reference scenario would include:

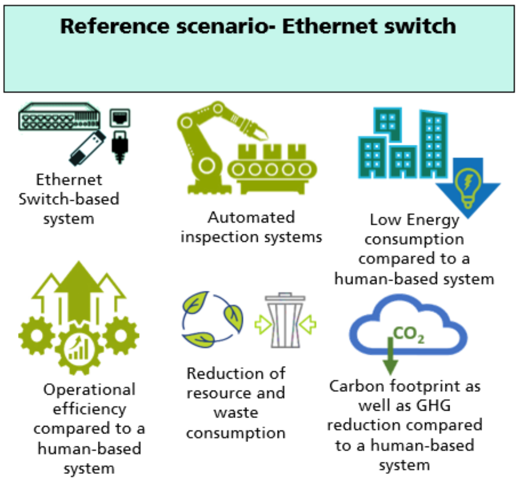


Figure 32: Ethernet switch-based reference scenario

In this scenario (**Figure 32**), industrial cameras and robotic arms are connected through Ethernet switches. The system already offers improvements over human-based inspection, such as lower energy consumption, better operational efficiency, and reduced resource and waste generation. It also contributes to a lower carbon footprint compared to manual processes.

However, when we compare this Ethernet-based setup with a PON-based optical network, several advantages emerge on the sustainability side. The PON system replaces power-hungry Ethernet switches with passive optical components such as OLTs and ONUs, which require significantly less operational energy. PON also has a lower embodied carbon footprint than Ethernet structure, considering the whole lifecycle of the use case. The on-premises hardware without centralised computing has higher energy usage, which can be reduced by the introduction of vPLCs. The lack of centralised optimisation results in inefficient energy usage. By transitioning to fiber-optics and edge cloud-based solutions, manufacturers can achieve significant improvements in efficiency, scalability, and sustainability, while also addressing workforce and environmental challenges.

4.1.3.3.11 Identifying additional second and higher-order effects of using the ICT solution

As discussed before, the main expected second-order effect (generic Consequence 2a. "Introduction of Automated Quality Assurance") is to replace the Ethernet switch-based Quality Assurance process by introducing an edge cloud computing-based automated Quality Assurance system.

Second-order impacts are the indirect environmental impacts resulting from the application of ICT solutions in non-ICT sectors, enabling them to operate more efficiently or sustainably. These impacts are often related to changes in behaviour, processes, or systems enabled by the technology. The second-order effects depict that the enhanced applications and efficiencies enabled by fiber-based solutions can increase energy efficiency and reduce the carbon footprint that can result from:

- Centralized edge cloud computing that results in system efficiency compared to traditional electrical switch-based system
- Automated quality assurance, which reduces resource consumption and enhances production efficiency
- Introducing advanced fiber networks enables cameras and robots to reduce energy consumption.

4.1.3.3.12 Identification of second-order effects of using the ICT solution

Table 29: Identification of second-order effects of using the ICT solution

No.	Consequence	Description	I/D
2a1a.	Removal of dedicated hardware (e.g., PLCs) through virtualization	Reduced emissions by removing PLC hardware	I
2a1b.	Higher Degree of Operational Efficiency	Difference between the energy consumption of robotic arms considering Ethernet switch vs PON scenario	I
2b1.	2b1. Evolution of the production of Ethernet-based ICT components (D)	To evaluate if introducing an optical solution has reduced the production of Ethernet-based ICT components	D

Note: I = Immediate, D = delayed

4.1.3.3.13 Identification of higher order effects

Table 30: Identification of higher-order effects

	Consequence	Description	I/D
3a1a.	Financial gains or losses by PON based solution seller	The vendor of the connected solution generates operating income linked to its sales, whose gains or losses are used in other parts of its business activity	I
3a1b.	Financial gains or losses by PON based solution user	The evolution in maintenance compared to the cost of implementing and managing the ICT system generates losses or gains for the user of the solution, which can be reused elsewhere	I
3b1.	Evolution of production volumes due to industry expansion	The adoption of smart factories may lead to increased production volumes, which may increase resource consumption as well as environmental impact unless managed sustainably.	D
3b2.	Development of ICT solutions for extra or improved purposes	Use of the smart ICT solution for further purposes (this could increase the data volume to be processed and transferred and production of more ICT components).	D
3b3.	New job markets	Improved connectivity may foster digital business models, thereby giving rise to new employment opportunities and strengthening industrial competitiveness.	D
4a.	Evolution of public popularity of smart cities and the Green ICT concept	(non-carbon effect)	D
4b.	Evolution of Digital Divide & Accessibility Issues	(non-carbon effect)	D

Note: I = Immediate, D = delayed

4.1.3.3.14 Identification of contextual factors

In general terms, contextual factors are the conditions or circumstances outside of which influence a system, process, or assessment. In the case of the Life Cycle Assessment (LCA) and the ITU-T L.1480, contextual factors are those expediting or impeding environmental impact assessment of ICT solutions; they could keep within the scope of the study, but are certainly not part of the said system. Contextual factors that can be potentially for the assessment are as elaborated.

Economic Factors:

- While the investment to change to PON networks may be pretty high. However, the long-term operational cost savings from this network can always make up for the initial capital.
- Availability of subsidies or tax benefits connected with PON-based industrial automation.

Structural Factors:

- The accuracy and reliability of any AI-based visual inspection system, dependent on the quality of the machine-learning models used for defect detection, continuous updating of the AI model, to add on various new designs introduced in production, and therefore different types of defects.
- Type of production line and frequency of quality checks performed.

Regulatory and Standards Contextual Factors:

- Compliance with Industry Standards
- Data Privacy and Security

Human and Behavioural Factors:

- Such considerations are the willingness of industries to shift from Ethernet switches to PON-driven quality control.
- The level of technical knowledge and support available for maintaining and troubleshooting the system.

4.1.3.3.15 Selection of effects to be quantified

Depending on the data availability, the quantifiable effects were selected.

4.1.3.3.16 Defining the system boundaries of the ICT solution scenario and the reference scenario

The identified effects and external factors are shown in the consequence tree below

4.1.3.4 Step 3 - Modelling, data collection and calculation

4.1.3.4.1 Data collection

4.1.3.4.1.1 Data collection for the reference scenario

In order to specify and quantify the reference scenario for an ex-ante study, information was collected primarily from literature references and also from interviews with the ICT vendor. The structure of the Ethernet switch-based system and the PON based system was developed by the Fraunhofer HHI F5G openLab research team, considering smooth operation and redundancy. Data related to the following aspects were collected:

- Carbon footprint data for components of Ethernet switch-based solution, i.e., core switch, aggregation switch, access switch, and optical module
- Carbon footprint data for components of PON-based solution, i.e., core switch, OLT, ONU, and optical module
- Product datasheet of the components to assess use-phase consumption
- Carbon footprint data of physical PLCs
- Carbon footprint data of vPLC; which is the data center consumption
- Percentage of the ICT components that need to be replaced during the lifetime

For GHG measurement using Life Cycle Assessment (LCA) methods, the ecoinvent 3.11 database was used.

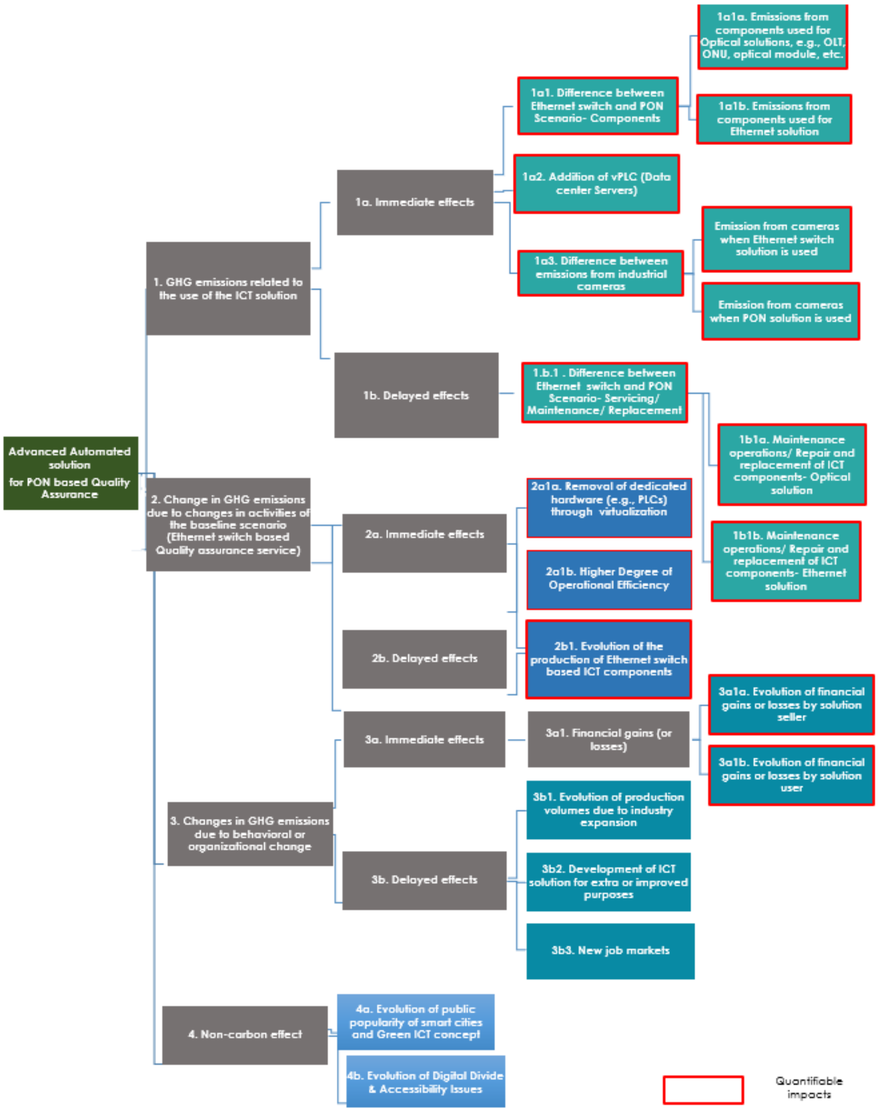


Figure 33: Consequence Tree for the study

4.1.3.4.1.2 Product Carbon Footprint- Ethernet switch-based solution

The required components for the Ethernet switch-based solution are listed as follows:

- **Core switch（24 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution, and end-of-life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor.

The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Core switch	2687	51.2	99,530	52.6	3,344

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **100GE QSFP28 optical module**

For raw material extraction, manufacturing, distribution and End of life data received from the ICT vendor is used for the assessment. Due to unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG estimation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production (KgCO2e)	Distribution (KgCO2e)	Use phase- 10 years (KgCO2e)	End of life (KgCO2e)	Power consumption/Component (Wh)
Optical module	1.21	0.004	104.17	0.004	3.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Aggregation switch（24 x 10GE SFP+, 2 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG assessment, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Aggregation switch	163	1.3	7,559.96	0.5	254

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Aggregation switch（48 x 10GE SFP+, 4 x 100GE QSFP28)**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use-phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production (KgCO2e)	Distribution (KgCO2e)	Use phase- 10 years (KgCO2e)	End of life (KgCO2e)	Power/Component (Wh)
Aggregation switch	163	1.3	8,661.22	0.5	291

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **10GE SFP+/28 optical module**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for GHG assessment of the use phase, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Optical module	1.21	0.004	44.65	0.004	1.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for the use-phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Access switch	112.5	0.6	2529.91	0.5	85

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.3.4.1.3 Data collection for the action scenario

Product Carbon Footprint- PON-based solution

- **Core switch (48 10GE SFP+)**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG estimation, which was required to develop the PON-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Core switch	2,687	51.2	10387.51	52.6	349

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **10GE SFP+ optical module**

For raw material extraction, manufacturing, distribution, and End of life data received from the ICT vendor is used for the assessment. Due to the unavailability of the specific product footprint data, data of a similar product was provided by the vendor. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG assessment, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Usephase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
Optical module	1.21	0.004	44.65	0.004	1.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

- **Optical Line Terminal (OLT)**

For raw material extraction, manufacturing, distribution, and end-of-life data received from the ICT vendor is used for the assessment. The maximum power consumption value from the data sheet of a product with the same configuration was used for use phase GHG calculation, which was required to develop the Ethernet switch-based structure. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power/Component (Wh)-OLT control boards (supporting 8 ports SFP+ per OLT)	Power/Component (Wh)-OLT uplink boards (24 ports SFP+; only 2 boards per OLT)	Power/Component (Wh)-OLT XGS-PON boards（16 ports SFP+; 4 boards per OLT used)
OLT	585.54	9.36	27,799.24	6.73	125	144	99

Note: For the use-phase GHG estimation, the total power consumption of the OLT boards was used.

- **Optical Network Unit (ONU) with 8x1GE ports**

For raw material extraction, manufacturing, distribution, and end-of-life data received from the ICT vendor is used for the assessment. For use-phase GHG estimation, real-time power consumption data from F5G openLab were collected for 10 days, and the average power consumption data is used for use-phase GHG estimation. Collected data per product for GHG estimation for the functional unit is as follows

Component name	Raw material acquisition and Production ($KgCO_2e$)	Distribution ($KgCO_2e$)	Use phase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/Component (Wh)
ONU	31.74	0.22	550.63	0.58	18.5

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.3.4.1.4 Data collection for Programmable Logic Controller (PLCs)

One PLC was considered for one VIS system. For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Source: Pérez-Martínez et al., 2021). For use-phase GHG estimation, power consumption data from the literature source were gathered. Collected data per product for GHG estimation for the functional unit is as follows

Component name	Production & Distribution(Kg CO2e)	Use phase- 10 years (KgCO2e)	Transport for EoL(Kg CO2e)	EoL(Kg CO2e)
PLC	15.55	1,040.596	2.85	-9.48

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.3.4.1.5 Data collection of virtual PLC consumption estimation (Data centre)

Lifecycle Stages	GHG ($KgCO_2e$)	Comments
Data centre without use phase (Scope: raw material supply (office supplies, water consumption), transportation (fuel consumption for vehicles), end-of-life treatment (where applicable for material inputs)	4.176 Kg CO_2e (considering Data centre area 2 sqm for 100 vms)	Literature Source: Üçtuğ and Ünver (2019); Modeled using Ecoinvent 3.11
Data centre without use phase for 1000 VISs and 10 servers	41.758	According to F5G openLab research, 100 vPLCs can be simultaneously running on one such Server that the current structure has, and thus with 10 Servers, the 1000 VIS would be covered. It is based on the requirements of the found commercial products, and the power Server models that we run in our own Edge Cloud.
Use phase of 10 years, considering 1 server for 100 VISs	5,000.291	Power consumption data collected from real-time monitoring from F5G open lab for 10 days and the average power consumption, i.e., 168.01 Wh, was considered for GHG estimation

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.3.4.1.6 Product Carbon Footprint- Industrial cameras

Ethernet-switch-based system

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Wazeem, 2022). The maximum power consumption value (i.e., 5.8 Wh) of the product (weight 100 g) of a similar configuration was used for usephase GHG calculation of the industrial camera. Collected data per product for GHG estimation for the functional unit is as follows

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase (estimation of 10 years)	172.63
EoL	0.003775
Total	205.14

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

PON system

For use-phase GHG estimation, real-time power consumption data from the F5G openLab were collected for 10 days, and the average power consumption data (i.e., 5Wh) is used (**Figure 34**).

Date	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05
Time	15:00:00	16:00:00	17:00:00	18:00:00	19:00:00	20:00:00	21:00:00	22:00:00	23:00:00
Average Power (W)	5	5	5	5	5	5	5	5	5

Figure 34: Example of real-time monitoring data of power consumption, collected from the F5G openLab

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the same literature source (Wazeem, 2022), that was used for the Ethernet-switch based reference scenario. Collected data per product for GHG estimation for the functional unit is as follows

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase from F5G Openlab data (estimation of 10 years)	148.82
EoL	0.003775
Total	181.33

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

4.1.3.4.1.7 Product Carbon Footprint- Robotic Arms

Ethernet-switch-based system

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the literature source (Wyatt et al., 2017). The maximum power consumption value (i.e., 180 Wh) of the product (weight 4 kg) of a similar configuration was used for use phase GHG calculation of the robotic arm. Collected data per product for GHG estimation for the functional unit is as follows:

Component name	Manufacturing ($KgCO_2e$)	Distribution ($KgCO_2e$)	Usephase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/ Component (Wh)
Robotic arm	39.55	0.28	5357.5	0.075	180

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

PON system

Collected data per product for GHG estimation for the functional unit is as follows

Component name	Manufacturing ($KgCO_2e$)	Distribution ($KgCO_2e$)	Usephase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Power consumption/ Component (Wh) from F5G openLab
Robotic arm	39.55	0.28	1192.25	0.075	40.06

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the same literature source (Wyatt et al., 2017) that was used for the reference scenario. For use-phase GHG measurement, real-time power consumption data from the F5G openLab were collected for 10 days (**Figure 35**), and the average power consumption data (i.e., 40.06 Wh) were used.

Date	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05	2025-06-05
Time	15:00:00	16:00:00	17:00:00	18:00:00	19:00:00	20:00:00	21:00:00	22:00:00	23:00:00
Average Power (W)	40.2	40.017	40.05	40.15	40.083	40,1	40.083	40.05	40.1

Figure 35: Example of real-time monitoring data of power consumption, collected from the F5G OpenLab

4.1.3.4.2 Quantifying the first order effects

Consequence 1a1.: Difference between Ethernet switch and PON Scenario- Components

The architecture of the Ethernet switch-based system and the PON based system was developed by the Fraunhofer HHI F5G openLab research team, considering smooth operation and redundancy. The listed components for the Ethernet switch solution are:

- Core switch（24 x 100GE QSFP28）
- 100GE QSFP28 Optical module
- Aggregation Switch（24 x 10GE SFP+, 2 x 100GE QSFP28)
- Aggregation Switch（48 x 10GE SFP+, 3 x 100GE QSFP28)
- 10GE SFP+/28 Optical module
- Access switch（24 x BASE-T 1 GE + 2 x SFP28 10GE)

Product carbon footprint data was collected from the ICT vendor, who provided data for similar types of products per quantity (discussed in section 4.1.3.4.1 "Data collection"). Use-phase data were collected from products of the same configuration used to develop the structure of the Ethernet switch-based solution by the F5G openLab research.

Table 31: GHG emission of Ethernet switch-based solution

Product requirements for 1000 VISs	Product Quantity	Raw material acquisition and Production	Distribution	Use	End of life	Total Kg CO_2e
Core switch（24 x 100GE QSFP28）	1	2,687	51.2	99,530	52.6	102,320
100GE QSFP28 Optical module	22	26.62	0.088	2,291.80	0.088	2,319
Aggregation Switch （24 x 10GE SFP+, 2 x 100GE QSFP28)	1	163	1.3	7,559.96	0.5	7,725
Aggregation Switch （48 x 10GE SFP+, 3 x 100GE QSFP28)	3	489	3.9	25,983.66	1.5	26,478
10GE SFP+/28 Optical module	336	406.56	1.344	15,000.87	1.344	15,410
Access switch（24 x BASE-T 1 GE + 2 x SFP28 10GE）	84	9,450	50.4	212,512.39	42	222,055
Total		13,222.18	108.232	362,878.293	98.032	376,306.74

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Therefore, the total GHG emission from the Ethernet switch-based ICT components was 376,306.74 Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Product requirements for 1000 VISs	Product Quantity	Raw material acquisition and Production	Distribution	Use (Energy source renewable energy)	End of life	Total Kg CO_2e
Core switch (24 x 100GE QSFP28)	1	2,687	51.2	21,249.61	52.6	24,040.41
100GE QSFP28 Optical module	22	26.62	0.088	489.30	0.088	516.096
Aggregation Switch (24 x 10GE SFP+, 2 x 100GE QSFP28)	1	163	1.3	1,614.055	0.5	1,778.85
Aggregation Switch (48 x 10GE SFP+, 3 x 100GE QSFP28)	3	489	3.9	5,547.52	1.5	6,041.92
10GE SFP+/28 Optical module	336	406.56	1.344	3,202.69	1.344	3,611.94
Access switch (24 x BASE-T 1 GE + 2 x SFP28 10GE)	84	9,450	50.4	45,371.48	42	54,913.88
Total		13,222.18	108.232	77,474,66	98.032	90,903.10

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission from the Ethernet switch-based ICT components was 90,903.10 Kg CO_2e when renewable energy is used for the use phase.

ICT components used for the PON solution (KgCO_2e)

The architecture of the PON-based system was developed by Fraunhofer HHI F5G openLab research team. The listed components for the PON solution are:

- Core switch (48 10GE SFP+)
- 10GE SFP+ optical module
- OLT control boards
- OLT uplink boards
- OLT XGS-PON boards
- ONU with 8x1GE ports
- Splitters (2:16) (8GE ONU 1:8(only two ports of the SPL to be used)

As discussed in the data collection chapter, product carbon footprint data was collected from the ICT vendor. For the optical module, the vendor provided data for similar types of products per quantity (discussed in data collection section 4.1.3.4.1.3 “Data collection for the action scenario”). Use-phase data were collected from real-time monitoring of the F5G openLab. For core switch and OLT use phase estimation, power consumption data of the same products was used to develop the structure by the F5G openLab research.

Table 32: GHG emissions of PON based solution

Product requirements for 1000 VISs	Quantity	Raw Material Extraction and Production	Distribution	Use phase	EoL	Total GHG $KgCO_{2e}$
Core switch (48 10GE SFP+)	3	8,061	153.6	31,162.53	157.8	39,535
10GE SFP+ optical module	200	242	0.8	8,929.092	0.8	9,173
OLT control boards (supporting 8 ports SFP+ per OLT; 2 boards per OLT, so 2 OLTs needed)*	4	1,171,08	18.72	55,598.48	13.46	56,802
OLT uplink boards (24 ports SFP+; only 2 boards per OLT, 2 OLTs needed)	4					
OLT XGS-PON boards（16 ports SFP+; 4 boards per OLT used, 2 OLTs needed)	8					
ONU with 8x1GE ports	250	7,935	405	137,656,83	145	146,142
Splitters（2:16）（8GE ONU 1:8）(only two ports of the SPL used)**	125					
Total		17,409.08	578.12	233,346.93	317.06	251,651.19

Note: *Total emissions of 2 OLTS are listed

** Emissions from Splitters were avoided as they don't consume power while operating

Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Therefore, the total GHG emission from the PON-based ICT components was 251,651.1935 Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Product requirements for 1000 VISs	Quantity	Raw Material Extraction and Production	Distribution	Use phase	EoL	Total GHG $KgCO_{2e}$
Core switch (48 10GE SFP+)	3	8,061	153.6	6653.21	157.8	15,025.61
10GE SFP+ optical module	200	242	0.8	1,906.36	0.8	2,149.96
OLT control boards (supporting 8 ports SFP+ per OLT; 2 boards per OLT, so 2 OLTs needed)*	4	1,171.08	18.72	11,870.297	13.46	13,073.557
OLT uplink boards (24 ports SFP+; only 2 boards per OLT, 2 OLTs needed)	4					
OLT XGS-PON boards（16 ports SFP+; 4 boards per OLT used, 2 OLTs needed)	8					
ONU with 8x1GE ports	250	7,935	405	29,389.788	145	37,874.788
Splitters（2:16）（ 8GE ONU 1:8）(only two ports of the SPL used)**	125					
Total		17,409.08	578.12	49,819.663	317.06	68,123.923

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission from the PON-based ICT components was 68,123.92 Kg CO2e when renewable energy is used for the use phase.

Difference:

Hence, shifting to PON from Ethernet switch can save (376,306.737- 251,651.194) or **124,655.543** Kg CO_2e GHG emissions, which is a **33.13%** savings. (**Figure 36**)

For the renewable energy scenario, shifting to PON can save (90,903.10- 68,123.923) or **22,779.18** Kg CO2e GHG emissions, which is a **25.06%** savings. (**Figure 36**)

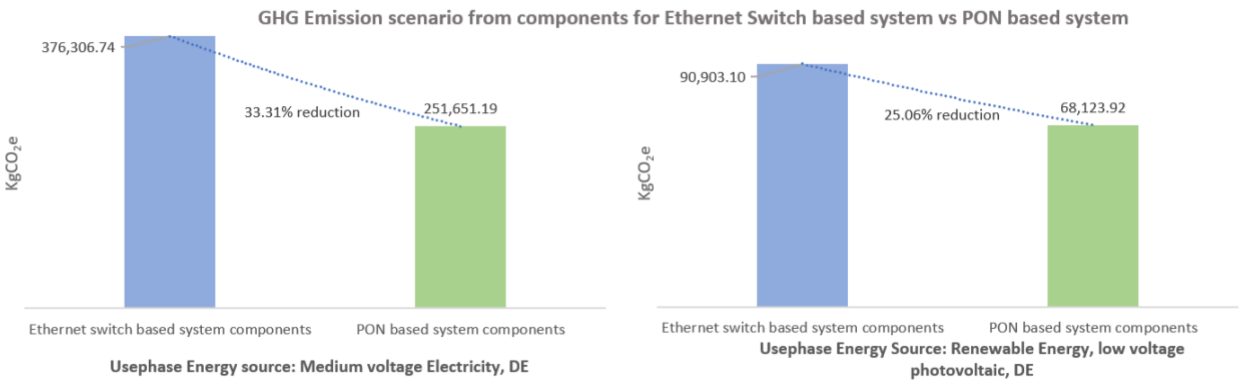


Figure 36: GHG Emission scenario from components for Ethernet Switch-based system vs PON-based system

Consequence 1a2.:_Emissions from vPLC- the Optical solution (Datacenter server)

Lifecycle Stages	GHG ($KgCO_2e$)	Comments
Data centre without use phase (Scope: raw material supply (office supplies, water consumption), transportation (fuel consumption for vehicles), end-of-life treatment (where applicable for material inputs)	4.176 Kg CO2e(considering Data centre area 2 sqm for 100 vms)	Literature Source: Üçtuğ and Ünver (2019); Modeled using Ecoinvent 3.11
Data centre without use phase for 1000 VISs and 10 servers	41.75765	According to F5G openLab research, 100 vPLCs can be simultaneously running on one such Server that the current structure has, and thus with 10 Servers, the 1000 VIS would be covered. It is based on the requirements of the found commercial products, and the power Server models that we run in our own Edge Cloud.
Usephase considering 1 server for 100 VISs	5,000.29	Power consumption data collected from real-time monitoring from F5G open lab
Usephase considering 10 VMs for 1000 VISs	50,002.91	

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Total emission from vPLC or Data centre for 1000 VISs is: (41.75765+50,002.91) = **50,044.672** $KgCO_{2e}$.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Lifecycle Stages	GHG ($KgCO_2e$)	Comments
Data centre without use phase (Scope: raw material supply (office supplies, water consumption), transportation (fuel consumption for vehicles), end-of-life treatment (where applicable for material inputs)	4.176 Kg CO2e(considering Data centre area 2 sqm for 100 vms)	Literature Source: Üçtuğ and Ünver (2019); Modeled using Ecoinvent 3.11
Data centre without use phase for 1000 VISs and 10 servers	41.75765	According to F5G openLab research, 100 vPLCs can be simultaneously running on one such Server that the current structure has, and thus with 10 Servers, the 1000 VIS would be covered. It is based on the requirements of the found commercial products, and the power Server models that we run in our own Edge Cloud.
Usephase considering 1 server for 100 VISs	1,067.564	Power consumption data collected from real-time monitoring from F5G open lab
Usephase considering 10 VMs for 1000 VISs	10,675.64	

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is (41.75765

+10,675.64) or **10,717.3997** CO_2e when renewable energy is used for the use phase; which can reduce 78.58% GHG emission compared to using of German medium voltage electricity during the operational phase (**Figure 37**).

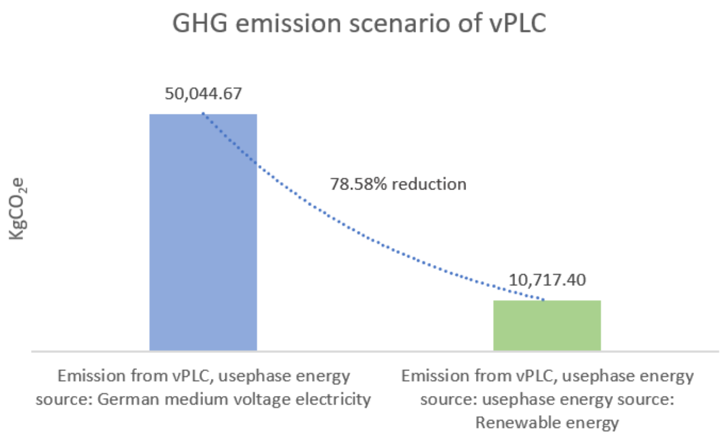


Figure 37: GHG emissions from vPLC

Consequence 1a3. Difference between emissions from industrial cameras

Ethernet-switch system

As discussed in data collection section 4.1.3.4.1.6 "Product Carbon Footprint- Industrial cameras", the collected data for one camera is as follows (Wazeem, 2022), Use phase data is from the F5G Open lab for the use case considering a 24/7 service and yearly working days 261.

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase from F5G Openlab data	172.63
EoL	0.003775
Total	205.14

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

So, for 1000 cameras, the total GHG emission is 205,143.098 Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase (Energy source renewable energy)	36.87
EoL	0.003775
Total	69.39

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 cameras is 69,386.63 Kg CO_2e when renewable energy is used for the use phase.

PON system

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the same literature source (Wazeem, 2022), that was used for the Ethernet-switch based reference scenario. For use-phase GHG estimation, real-time power consumption data from the F5G openLab were collected for 10 days, and the average power consumption data (i.e., 5Wh) is used. Collected data per product for GHG estimation for the functional unit is as follows

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase from F5G Openlab data (estimation of 10 years)	148.82
EoL	0.003775
Total	181.33

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

So, for 1000 cameras, the total GHG emission is 181,330.727 Kg CO_2e.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Lifecycle stages	GHG emission (Kg CO_2e)
Raw material + Production+ Transport	32.51
Use phase (Energy source renewable energy)	31.77
EoL	0.003775
Total	64.29

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 cameras is 64,285.27 Kg CO_2e when renewable energy is used for the use phase.

Difference:

Hence, shifting to PON from Ethernet switch can save (205,143.098 - 181,330.727) or **23,812.37** Kg CO_2e GHG emissions, which is a **11.61%** savings. (**Figure 38**)

For the renewable energy scenario, shifting to PON can save (69,386.63- 64,285.27) or **5,101.36** Kg CO2e GHG emissions, which is a **7.35%** savings. (**Figure 38**)

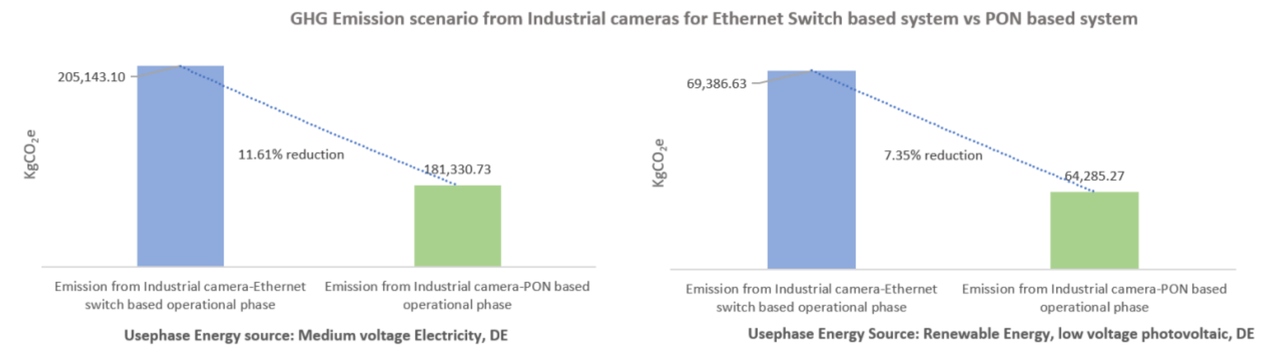


Figure 38: GHG Emission scenario from Industrial cameras for Ethernet Switch-based system vs. PON-based system

Consequence 1b1. Difference between Ethernet switch and PON scenario - Servicing/ Repair and Replacement

It is a delayed impact. The calculation was done using proxy data to figure out the percentage of the Ethernet switches that need to be replaced during the lifetime of the components and the data was gathered from an ICT vendor for ICT equipment.

For 10 years of the lifecycle of the proxy ICT component, the proxy data shows a failure rate of <0.3% during that lifecycle.

Hence, for the core switch, GHG emission for maintenance: (0.3%* 102,320) or 306.96 kgCO2e

For Aggregation switches, GHG emission for maintenance:

(0.3% * 7,725) or 23.17 KgCO_2e and (0.3% * 26,478) or 79.43 KgCO_2e

For Access switches, GHG emission for maintenance: (0.3% * 222,055) or 666.16 kgCO_2e

Therefore, the total estimated emission from maintenance of Ethernet switch components for 10 years of operational service is (306.96 + 23.17 + 79.43 + 666.16) or 1,075.73 kgCO_2e.

From the ICT vendor, the collected information for PON components:

For OLTs, the lifecycle is 15 years, with a failure rate of <0.5% during that lifecycle.

For ONU, the lifecycle is 10 years, with a failure rate of <0.3% during that lifecycle.

For the core switch, the calculation was done using proxy data (i.e., failure rate of <0.3%) to figure out the percentage of the Ethernet switches that need to be replaced during the lifetime of the components, and the data was gathered from an ICT vendor for ICT equipment.

Hence, for the core switch, GHG emission for maintenance using proxy data: 0.3%* 39,534.93053 = 118.6045 kgCO2e

For OLTs, GHG emission for maintenance:0.33% * 56,801.74= 187.45 KgCO_2e (failure rate of <0.5% for 15 years, then for 10 years it's 0.33%)

For ONUs, GHG emission for maintenance: 0.3% * 146,141.8326= 438.43 kgCO_2e

Therefore, the total estimated emission from maintenance of ICT components for 10 years of operational service is (118.6045 + 187.45 + 438.43) or 744.48 kgCO_2e.

Optical vs Ethernet	Optical vs Ethernet- Details	GHG $KgCO_{2e}$	Difference GHG $KgCO_{2e}$
1b1. Difference between Ethernet and Optical Scenario- Servicing/ Maintenance	1b1a. Maintenance operations/ Repair and replacement of ICT components- Optical solution	744.48	331.26
	1b1b. Maintenance operations/ Repair and replacement of ICT components- Ethernet solution	1,075.73	

Difference:

Hence, shifting to PON hardware can save maintenance emissions of **331.26** Kg CO2e GHG emissions, which is a 30.79% savings.

4.1.3.4.3 Quantify the second-order effects

Consequence 2a1a.: Reduction of emissions by the removal of dedicated hardware (e.g., PLCs)

Programmable Logic Controller (PLC) Hardware:

As discussed in the data collection section 4.1.3.4.1.5 "Data collection of virtual PLC consumption estimation", product footprint and use phase data for the PLC were collected from a literature source (Pérez-Martínez et al., 2021). Use phase power consumption data was found in the source; it was modelled using the ecoinvent 3.11 database.

	Production & Distribution	Usephase	Transport for EoL	EoL	Total $KgCO_{2}e$
PLC (1 item for 5 years of use phase) (Pérez-Martínez et al., 2021)	15.55		2.85	-9.48	
PLC (1 item for 10 years of use phase)	15.55	1040.596	2.85	-9.48	1049.52
PLC (1000 items for 10 years of use phase)	15,550	1,040,595.81	2850	-9480	1,049,515. 81

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Again, the calculation was also done using renewable energy as an energy source for the use phase.

	Production & Distribution	Usephase	Transport for EoL	EoL	Total KgCO2e
PLC (1 item for 5 years of use phase) (Pérez-Martínez et al., 2021)	15.55		2.85	-9.48	
PLC (1 item for 10 years of use phase)	15.55	222.27256	2.85	-9.48	231.19256
PLC (1000 items for 10 years of use phase)	15550	222,272.56	2850	-9480	231,192.56

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is 231,192.56 Kg CO_2e when renewable energy is used for the use phase.

Virtual PLC (vPLC)/ Data center consumption:

Lifecycle Stages	GHG (KgCO₂e)	Comments
Data centre without use phase (Scope: raw material supply (office supplies, water consumption), transportation (fuel consumption for vehicles), end-of-life treatment (where applicable for material inputs)	4.176 Kg CO2e(considering Data centre area 2 sqm for 100 vms)	Literature Source: Üçtuğ and Ünver (2019); Modeled using Ecoinvent 3.11
Data centre without use phase for 1000 VISs and 10 servers	41.75765	According to F5G openLab research, 100 vPLCs can be simultaneously running on one such Server that the current structure has, and thus with 10 Servers, the 1000 VIS would be covered. It is based on the requirements of the found commercial products, and the power Server models that we run in our own Edge Cloud.
Usephase considering 1 server for 100 VISs	5,000.291	Power consumption data collected from real-time monitoring from F5G open lab
Usephase considering 10 VMs for 1000 VISs	50,002.91432	

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Total emission from vPLC or Data centre for 1000 VISs is: (41.75765022+50,002.91432) = 50,044.672 $KgCO_{2e}$.

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Lifecycle Stages	GHG ($KgCO_2e$)	Comments
Data centre without use phase (Scope: raw material supply (office supplies, water consumption), transportation (fuel consumption for vehicles), end-of-life treatment (where applicable for material inputs)	4.176 Kg CO2e(considering Data centre area 2 sqm for 100 vms)	Literature Source: Üçtuğ and Ünver (2019); Modeled using Ecoinvent 3.11
Data centre without use phase for 1000 VISs and 10 servers	41.75765	According to F5G openLab research, 100 vPLCs can be simultaneously running on one such Server that the current structure has, and thus with 10 Servers, the 1000 VIS would be covered. It is based on the requirements of the found commercial products, and the power Server models that we run in our own Edge Cloud.
Usephase considering 1 server for 100 VISs	1,067.564	Power consumption data collected from real-time monitoring from F5G open lab
Usephase considering 10 VMs for 1000 VISs	10,675.64	

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is (41.75765022 +10,675.64) or 10,717.3997 CO_2e when renewable energy is used for the use phase

Difference:

Hence, shifting to vPLC from PLC hardware can reduce (1,049,515.81- 50,044.672**)** or **1,038,798.4**1Kg CO2e GHG emissions, which is a 95.23% savings (**Figure 39**).

For the renewable energy scenario, shifting to vPLC from PLC hardware can reduce (231,192.56-10717.3997) or **220,475.16** Kg CO2e GHG emissions, which is a 95.36% savings (**Figure 39**).

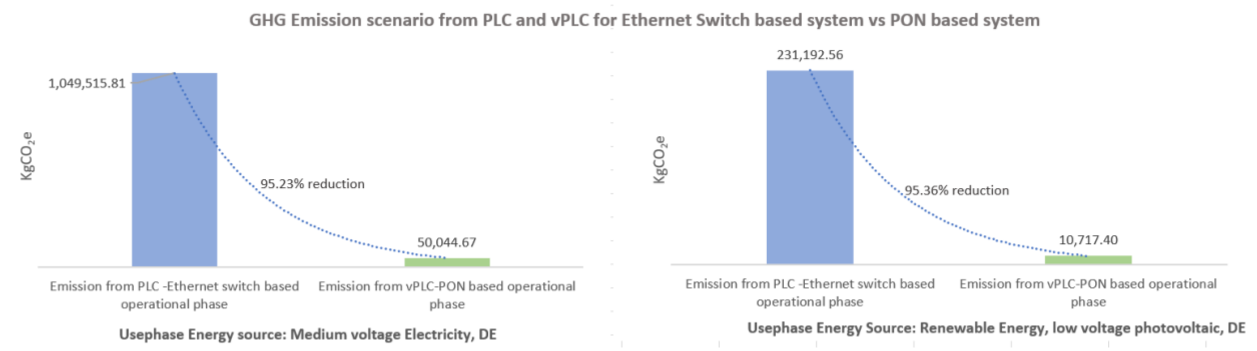


Figure 39: GHG Emission scenario from PLC and vPLC for Ethernet Switch-based system vs PON-based system

Consequence 2a2b.: Higher Degree of Operational Efficiency

This is the difference between the emissions from the robotic arm, considering the reference scenario and the use case, which contributes to increasing the efficiency further.

Ethernet-switch system

As discussed in the data collection section 4.1.3.4.1.7 "Product Carbon Footprint- Robotic Arms", product data for the Composite Double-Arm Type Robotic Arm was collected from a literature source (Wyatt et al., 2017). For the use phase, data is from the F5G Open lab for the use case considering a 24/7 service and yearly working days of 261.

	Manufacturing	Transportation	Use phase	End of Life	Total $kgCO_2e$
For 1 Robotic arm	39.54717	0.283777	5357.50	0.0749973	5397.41
For 1000 robotic arms	39547.17	283.777	5,357,500.38	74.9977	5,397,406.32

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Again, the calculation was also done using renewable energy as an energy source for the use phase.

	Manufacturing	Transportation	Use phase (Energy source: renewable energy)	End of Life	Total $kgCO_2e$
For 1 Robotic arm	39.547169817	0.28377	1144.37	0.0749973	1184.27
For 1000 robotic arms	39547.16981	283.773	1,144,368.73	74.997	1,184,274.67

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is 1,184,274.67 Kg CO_2e when renewable energy is used for the use phase.

PON system

For raw material extraction, manufacturing, distribution, and end-of-life data were collected from the same literature source (Wyatt et al., 2017) that was used for the reference scenario. For use-phase GHG measurement, real-time power consumption data from the F5G openLab were collected for 10 days, and the average power consumption data were used. Collected data per product for GHG estimation for the functional unit is as follows

Component name	Manufacturing ($KgCO_2e$)	Distribution ($KgCO_2e$)	Usephase- 10 years ($KgCO_2e$)	End of life ($KgCO_2e$)	Total $kgCO_2e$
For 1 Robotic arm	39.55	0.28	1192.25	0.075	1232.15
For 1000 robotic arms	39547.16981	283.773	1,192,244.36	74.997	1,2321,52.299

Note: Selected process from LCA database (Ecoinvent 3.11) for use phase: electricity, medium voltage-DE

Again, the calculation was also done using renewable energy as an energy source for the use phase.

Component name	Manufacturing	Transportation	Usephase (Energy source: renewable energy)	End of Life	Total $kgCO_2e$
For 1 Robotic arm	39.547	0.283773	254.55	0.0749973	294.45
For 1000 robotic arms	39,547.16981	283.773	254,545.07	74.997	294,451.01

Note: LCA database (Ecoinvent 3.11) for use phase- electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | Cutoff, U-DE

Therefore, the total GHG emission for 1000 VISs is 294,451.01 Kg CO_2e when renewable energy is used for the use phase.

Reduction/ Increased efficiency:

Hence, shifting to PON can save (5,397,406.32- 1,232,152.299) or **4,165,254.025** kg CO_2e GHG emissions, which is a **77.17%** savings (**Figure 40**).

When renewable energy is used for the use phase, the PON system can save (1,184,274.67- 294,451.01) or **889,823.66** kg CO_2e GHG emissions, which is a **75.14%** savings (**Figure 40**)

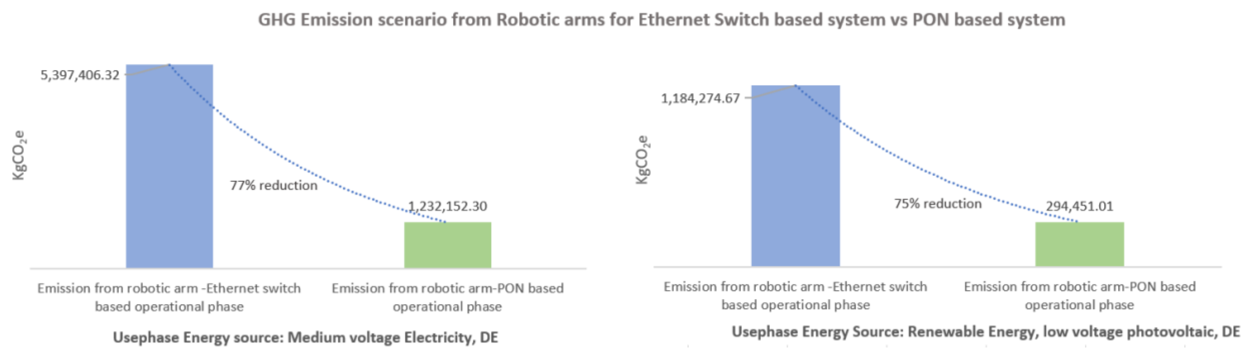


Figure 40: GHG Emission Reduction of Robotic arms from shifting to PON-based system

Consequence 2.b.1: Evolution of the production of Ethernet-based ICT components

It is a delayed effect and will be estimated in the next release of the report.

4.1.3.4.4 Assessment of higher-order effects including quantification

In this ex-ante study, higher-order impacts were identified in section 4.1.3.3.13 "Identification of higher order effects" and will be estimated in the next release of the report.

4.1.3.5 Results presentation and analysis

4.1.3.5.1 Results

Consequences (Human-based vs Ethernet switch-based)	GHG Value	%	% per order
1a1. Difference between Ethernet switch and PON Scenario-Components (I)	124,655.543	2.307%	3.68%
1a2. Addition of vPLCs	50,044.672	0.926%	
1a3. Difference between emissions from industrial cameras	23,812.37	0.44%	
1b1. Difference between Ethernet switch and PON Scenario-(Servicing/Repair and Replacement)	331.26	0.006%	
2a1a. Reducing emissions by the removal of dedicated hardware (e.g., PLCs) (I)	-1,038,798.41	19.23%	96.32%
2a1b. Higher Degree of Operational Efficiency (I)	- 4,165,254.025	77.09%	
2b1. Evolution of the production of Ethernet based ICT components (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
2b2. Evolution of the production of company vehicles (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
3a1a. Evolution of financial gains or losses by the solution seller and user (I) 3b1. Evolution of production volumes due to industry expansion (D) 3b2. Development of ICT solution for extra or improved purposes (D) 3b3. New job markets (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
Total (kgCO_2e)	−5,005,208.59		
Total absolute value	5,402,896.28		

Note: I = Immediate, D = delayed

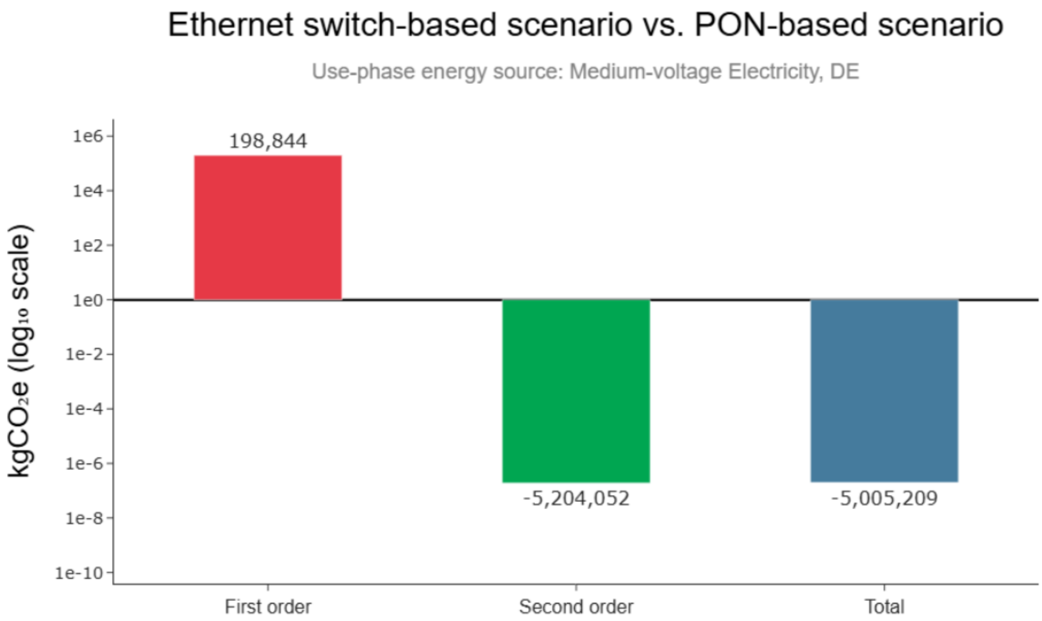


Figure 41: GHG emissions over 10 years

In addition, the table below shows GHG emission scenario when renewable energy is used in the use phase.

Consequences (Human-based vs Ethernet switch-based)	GHG Value	%	% per order
1a1. Difference between Ethernet switch and PON Scenario- Components (I)	22,779.181	1.982%	3.39%
1a2. Addition of vPLCs	10,717.3997	0.932%	
1a3. Difference between emissions from industrial cameras	5,101.36	0.44%	
1b1. Difference between Ethernet switch and PON Scenario- (Servicing/Repair and Replacement)	331.26	0.029%	
2a1a. Reducing emissions by the removal of dedicated hardware (e.g., PLCs) (I)	-220,475.16	19.18%	96.61%
2a1b. Higher Degree of Operational Efficiency (I)	- 889,823.66	77.43%	
2b1. Evolution of the production of Ethernet based ICT components (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
2b2. Evolution of the production of company vehicles (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
3a1a. Evolution of financial gains or losses by the solution seller and user (I) 3b1. Evolution of production volumes due to industry expansion (D) 3b2. Development of ICT solution for extra or improved purposes (D) 3b3. New job markets (D)	This is a delayed effect; accurate calculation will be provided in the next release of the report	This is a delayed effect; accurate calculation will be provided in the next release of the report	
Total ($kgCO_2e$)	−1,071,369.62		
Total absolute value	1,149,228.0207		

Note: I = Immediate, D = delayed

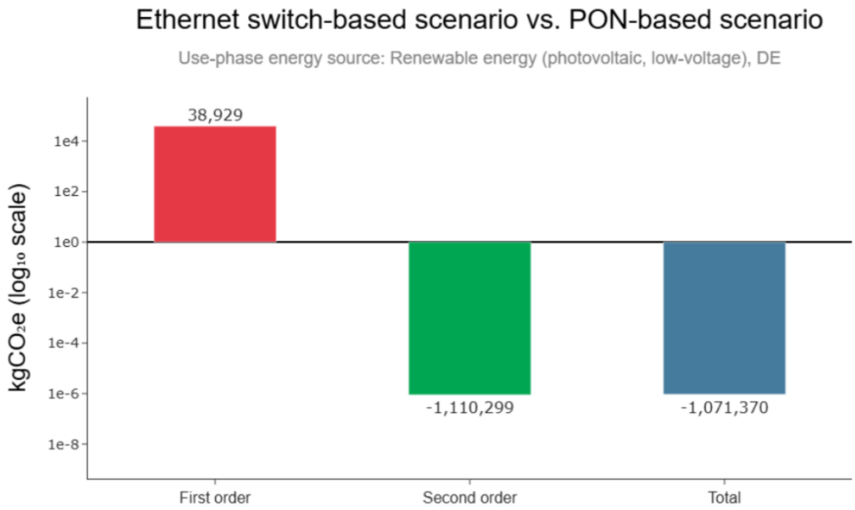


Figure 42: GHG emissions over 10 years, when renewable energy is used during the operational phase

4.1.3.5.2 Analysis of results

4.1.3.5.2.1 Disclaimer

The present study is conducted at a "Tier3" level of precision, particularly in view of its "ex-ante" nature, which requires us to imagine future usage and user behavior.

Under these conditions, it should be remembered that, about the scope and quality of the assessment obtained, Recommendation L.1480 states that the Tier 3 assessments "are the simplest assessments and are not considered rigorous" (§.10.1.2), provide a « screening / first approximation » (§.10.1.2 table 2) which "can only give initial guidance on the effect of ICT solutions" (§.13.3.2 and §.10.5 on reporting), thus "shall not be used for public or consumer communication" (§.13.3.2) and "should not be used as a sole input for [decision-making]" (Note on §.10.5).

With regard to the assessment process, "the establishment of the consequence tree [is] … recommended for Tier 3 assessments » (§.10.2), and "Tier 3 assessments should include all the effects in a consequence tree before any limitation or cut-off associated with the depth of the assessment and the chosen functional unit is performed" (§. 10.2.6), finally "Tier 3 assessments should consider net second order effects and should identify contextual factors and higher order effects. These are the simplest assessments and are not considered rigorous" (§.10.1.2).

4.1.3.5.2.2 Contribution to decarbonization

Subject to the above reservations Section 5.5.2.1 "Disclaimer", the use from 2025 of the ICT solutions for Edge cloud-based automated visual inspection systems (VIS) to reduce its carbon footprint by reducing GHG emissions by replacing Ethernet switch-based visual inspection systems.

- emissions reduction of 5,005.21 TCO_2e over the 10-year operational lifetime of the VISs,
- emissions reduction of 1,071.37 TCO_2e over the 10-year operational lifetime of the VISs when renewable energy is used during the operational phase.

4.1.3.5.2.3 Importance of standards and certification

However, these improvements can only be realized if the measurement data generated by the system is proven to be sufficiently reliable to meet certification and compliance requirements. This also depends on relevant standards and regulations being updated to accept such measurement methods, and on the system successfully achieving formal certification. Only then can automated measurement processes legitimately replace conventional inspections.

Therefore, the essential first step within the quality assurance framework is to obtain certification for the proposed solution, ensuring it can be integrated into manufacturing operations while maintaining product quality and reducing operational impacts, including emissions.

4.1.3.5.2.4 Proportion of different effect classes

Here, the proportion in the balance on GHG emissions would be 3.68% due to the ICT solution itself (first-order effect) and 96.32% (second-order effect). Higher order impact proportion will be added in the next release of the report.

When renewable energy is considered, the proportion in the balance on GHG emissions would be 3.39% due to the ICT solution itself (first-order effect) and 96.61% (second-order effect). Higher order impact proportion will be added in the next release of the report.

4.1.3.4.6 Scaling up

The present study assumes 1000 VIS stations in the context of a large manufacturing industry. Scaling up will be added in the next release of the report.

4.1.3.5 Step 4 - Interpretation of results

4.1.3.5.1 Evaluation of the applied method

The Tier3 level of precision described in Recommendation L.1480 has been applied, as is natural for an *ex-ante* evaluation in which, by definition, the uses of the ICT solution are not known with any precision, and even more so in the case of a new solution which is not active with any customer/user of the type studied.

4.1.3.5.2 Data quality analysis

Data relating to the use case has been obtained from literature sources and interviews with the ICT vendor. For use-phase operation of the PON scenario, primary real time was collected from Fraunhofer HHI F5G openLab. They can be considered sufficient and reliable for the desired Tier 3 level of analysis.

Generic data were obtained from various online sources and available literature.

4.1.3.5.3 Sensitivity analysis

The result depends entirely on the existence of standardization that recognizes the possibility of using data received from the ICT solution equipment to reduce GHG emissions of the quality assurance process in manufacturing industries.

The results of the visual-inspection use case are sensitive to several assumptions that affect both first-order and second-order GHG impacts. Factors include the power consumption of cameras, edge-processing devices, and network infrastructure (Ethernet switch or PON), ICT-device lifetime, and the accuracy of defect detection. Adjusting these parameters within plausible ranges demonstrates that the overall GHG reduction potential may vary significantly, especially when inspection accuracy or ICT electricity consumption changes. Therefore, standardization, data acceptance policies, and operational parameters of the ICT system play a decisive role in determining the robustness of the final GHG-impact outcome.

4.1.3.5.4 Uncertainty analysis

The uncertainty of the visual-inspection use case arises from data-quality limitations, variability in ICT equipment operation, differences between manufacturer specifications (where data from product data sheet was used) and real-world operation and methodological choices.

Key uncertainties include ICT energy-consumption data, the accuracy of defect detection, the operational duty cycle of cameras and processing hardware. Additional uncertainty stems from equipment lifetime assumptions and grid-emission-factor fluctuations.

The uncertainties influence both first-order and second-order results and highlight the need for further real-world measurement data and standardization of digital QA protocols.

4.1.3.6 Step 5 - Reporting

The study is reported aligning with the ITU-T L.1480 reporting format.

4.1.3.7 Step 6 - Critical review

Critical review ensures compliance with methodological requirements and increase the credibility and reliability of the LCA results. The main purpose is to conduct an impartial evaluation of the LCA study in compliance with ITU-T L.1480 standards to assure consistency between a life cycle assessment and the concepts and criteria of the International Standards on life cycle assessment. According to ITU -T L. 1480 recommendation, depending on the aim of the assessment, critical review may be recommended or required. It also states that if compliance with this Recommendation is claimed, practitioners are encouraged to share the report with the ITU-T SG5 Secretariat (tsbsg5@itu.int) for reference.

Besides, if the study aims to support a comparison claim for public disclosure, interested parties need to perform this evaluation as a critical review. The scope includes a concise overview of the LCA study, detailing the ICT system, functional unit, and system boundaries under consideration.

The internal review of the document has been conducted while implementing the assessment. This document has also been reviewed by AIOTI WG GIE.

4.1.3.8 References for use case "Edge-cloud based visual inspection for automated Product Quality assessment"

AIOTI WG Standardisation. (2024). Computing continuum scenarios, proof of concepts, requirements and optical communication enablers (Release 2.0). AIOTI. https://aioti.eu/wp-content/uploads/AIOTI-Computing-Continuum-Report-R2-Final.pdf

EspoCRM. (2025, March 13). How many work days in a year? (2025) Updated. https://www.espocrm.com/blog/how-many-work-days-in-a-year/

Pérez-Martínez, M. M., Carrillo, C., Rodeiro-Iglesias, J., Soto-Benéitez, B., Dominguez, A., Vilela, I., & Lavín, A. G. (2021). *Life cycle assessment of repurposed waste electrical and electronic equipment: A case study*. *Sustainable Production and Consumption, 27*, 1637–1649. https://doi.org/10.1016/j.spc.2021.03.017

Statistics Canada. (2007). *A portrait of seniors in Canada: Highlights from the 2006 Census* (Catalogue No. 11-402-X). https://www150.statcan.gc.ca/n1/pub/11-402-x/2007/4005/ceb4005_002-eng.htm

Üçtuğ, F. G., & Ünver, T. C. (2023). Life cycle assessment-based environmental impact analysis of a tier 4 data center: A case study in Turkey. Sustainable Energy Technologies and Assessments, 56, 103076. https://doi.org/10.1016/j.seta.2023.103076

Wazeem, A. (2022). Life cycle assessment of a camera system: A case study (Master's thesis, [University name]). DiVA – Digitala Vetenskapliga Arkivet. https://www.diva-portal.org/smash/get/diva2:1736686/FULLTEXT01.pdf

Wyatt, H., Wu, A., Thomas, R., & Yang, Y. (2017). *Life cycle analysis of double-arm type robotic tools for LCD panel handling*. Machines, 5(1), 8. https://doi.org/10.3390/machines5010008

4.2 Cross-domain use cases

As introduced in Section 3.2, the cross-domain use cases that are used in the current version of this report are focusing on the concept of [Positive Energy Districts (PED)](). The basic principle of a PED is to create an area within the city boundaries, capable of generating more energy than is used, and agile/flexible enough to respond to energy market variations. Rather than simply achieving an annual net energy surplus, it should also support minimizing impacts on the connected centralized energy networks by offering options for increasing onsite load-matching and self-use of energy, technologies for short- and long-term energy storage, and providing energy flexibility with smart control.

4.2.1 GHG impact assessment of "Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)" use case

This section provides GHG impact assessment of the Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations use case using the revised ITU-T L.1480 recommendation.

All principal quantitative parameters have been verified against primary or authoritative secondary sources. The greenhouse-gas reduction figure (≈ 92–95 %) remains valid within a ±3 % sensitivity range.

A brief overview of this use case is described in Section 3.2.1.1 of this report.

***Disclaimer:* The GHG emissions assessment process and results described in this section are preliminary and are partially aligned with the revised ITU-T L.1480 methodology. It is expected that the next version(s) of this report will include an accurate assessment alignment with the revised ITU-T L.1480 methodology.**

Executive Summary

Key Environmental Impact

This assessment demonstrates that the SMADE (Smart Monitoring and Actions for optimal Delivery of Electricity) system enables a 92-95% reduction in greenhouse gas (GHG) emissions for ferry electrification on the Stornes-Bjørnerå route, representing an annual avoidance of approximately 2,485 ± 247 tonnes CO_2 equivalent. This finding is based on a comprehensive ITU-T L.1480 Tier 2 assessment comparing diesel-powered and electric ferry operations over a 25-year lifecycle period.

Technical and Economic Performance

The SMADE system delivers multiple co-benefits beyond emissions reduction:15% improvement in energy efficiency through optimized charging patterns,8% operational efficiency gain from predictive maintenance, and12% renewable energy optimization through smart grid integration. The ICT solution investment demonstrates positive economic returns with a 6.2-year payback period and €3.8 million net present value over the assessment period.

Methodology and Compliance

This assessment follows the complete ITU-T L.1480 "Enabling the Net Zero transition" Tier 2 methodology (December 2022), implementing all seven required assessment steps with comprehensive effect categorization. The analysis encompasses first-order effects (SMADE ICT system infrastructure), second-order effects (ferry electrification and operational changes), and higher-order systemic impacts including rebound effects and supply chain implications. Quantification includes a ±3% uncertainty analysis and sensitivity testing across key parameters including Norwegian grid carbon intensity (18-25 g CO_2e/kWh), battery lifecycle emissions (55-90 kg CO_2e/kWh), and operational scenarios.

Policy and Sectoral Implications

The findings support Norway's Zero-Emission Fjords mandate (effective 2026) and demonstrate substantial progress toward maritime decarbonization goals. The SMADE solution addresses critical infrastructure challenges for ferry electrification, particularly the constrained 10-15 minute charging windows during passenger/vehicle loading. Results indicate potential for scaling across Norway's extensive ferry network (approximately 200 routes), suggesting system-wide GHG reductions exceeding 400,000 tonnes CO_2 equivalent annually if deployed at scale. The assessment validates ICT-enabled approaches as essential infrastructure for maritime electrification and provides quantitative evidence for policy support and investment decisions in sustainable transport technologies.

Keywords: Ferry electrification, ICT-enabled GHG reduction, SMADE system, ITU-T L.1480, maritime decarbonization, smart charging infrastructure, Norwegian Zero-Emission Fjords

4.2.1.1 Introduction

This supplement illustrates the implementation of the main steps of the assessment methodology described in ITU-T Recommendation L.1480 [ITU-T L.1480]. It presents a "Tier 2" evaluation relating to an ex-ante case study of implementing an Energy Management System (EMS) for a fully electric ferry operating on the Stornes–Bjørnerå route in the Troms region, Norway.

The assessment examines the deployment of SMADE (Smart Monitoring and Actions for optimal Delivery of Electricity) solution to enable grid-friendly electrification of maritime transport while reducing diesel dependency and associated greenhouse gas (GHG) emissions. The ICT solution integrates real-time monitoring, predictive analytics, battery state-of-charge optimisation, and smart charging infrastructure to transform ferry operations from fossil-based to electric propulsion.

4.2.1.2 Key Assumptions and Considerations

The following assumptions are organized into four logical groups: (1) Technical and Performance Framework, (2) Operational Context and Service Patterns, (3) Methodological Boundaries, and (4) Policy and Market Context. This structure consolidates related assumptions while preserving all technical details.

This document focuses on GHG emissions attributable to technical configurations—batteries, propulsion, energy management, and charging infrastructure—each of which undergoes major renewal long before the hull reaches obsolescence. Thus, the chart will either capture the emission-intensive lifecycle of replaceable subsystems, or the vessel's entire structural life.

In Norwegian maritime practice, particularly for robust steel-hulled ferries operating in coastal or sheltered routes, the physical hull life often extends to 60–80 years, sometimes even longer with proper refits and class renewals.

4.2.1.2.1 Technical and Performance Framework (consolidated)

In greenhouse-gas (GHG) assessments such as those following the ITU-T L.1480 and DNV GL LCA guidelines, the functional lifetime typically reflects the economic or technological relevance of the asset rather than its ultimate structural limit. For electric ferries, this is often defined by the period before a full system modernisation or hull repurposing occurs.

4.2.1.2.2 Operational Context and Service Patterns (consolidated)

Norwegian counties (e.g., Vestland, Nordland, Møre og Romsdal) commonly tender ferry operations on 10–15-year contracts, after which vessels are refurbished or reassigned. For carbon-accounting purposes, the "use phase" in many SMADE-type analyses is truncated to a 25–30-year operational envelope, corresponding to two contract cycles.

4.2.1.2.3 GHG Boundary Framework (part of Technical Framework)

This SMADE document focuses on GHG emissions attributable to technical configurations—batteries, propulsion, energy management, and charging infrastructure—each of which undergoes major renewal long before the hull reaches obsolescence. Thus, the chart will either capture the emission-intensive lifecycle of replaceable subsystems, or the vessel's entire structural life.

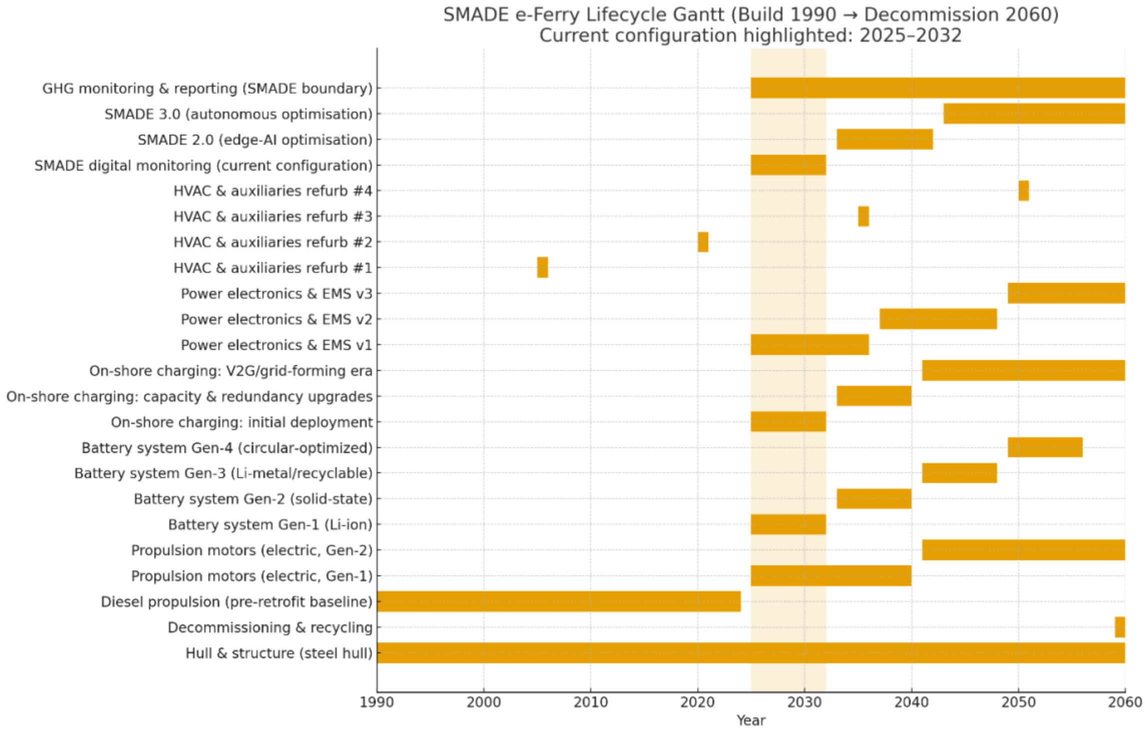


Figure 43: ***lifecycle Gantt covering a ferry built in 1990 and decommissioned in 2060 (≈70 years***

Table 33: Assumptions for the Gantt baseline

Parameter	Assumed value	Rationale
Build & commissioning year	2025	Inferred from SMADE timeline and ferry electrification pilot period.
Expected lifetime	25 years (2025–2050)	Aligns with standard Norwegian ferry renewal cycles and classification society guidelines (DNV, 2023).
Mid-life refit interval	Every 8–10 years	Reflects typical maritime overhaul cycles.
Battery replacement interval	7–8 years	Based on empirical degradation rates (DNV GL Maritime Battery Report 2022).
Power electronics and propulsion updates	10–12 years	Reflects control system and inverter upgrades.
Hull and superstructure	25 years	Standard structural longevity under regular maintenance.
Operational configuration (current)	2025–2032	Period with today's SMADE-tested configuration (first-generation battery, standard grid interface).

Table 34: Ferry Lifecycle Planning Parameters and Assumptions

Parameter	Assumed Value	Rationale	Primary Source
Build & commissioning year	2025	Aligned with SMADE project timeline and Norwegian ferry electrification pilot programs	SMADE Project Documentation (2025)
Expected lifetime	25 years (2025-2050)	Standard for Norwegian ferry operations; aligns with classification society guidelines and public tender cycles	DNV GL Maritime Guidelines 2023; Norwegian Public Roads Administration
Mid-life refit interval	Every 8–10 years	Reflects typical maritime overhaul cycles.	
Battery replacement interval	7-8 years	Based on empirical degradation rates in marine environments and warranty periods for marine-grade LFP systems	DNV GL Maritime Battery Report 2022; manufacturer specifications
Power electronics and propulsion updates	7–8 years	Reflects control system and inverter upgrades.	
Hull and superstructure	10–12 years	Reflects control system and inverter upgrades.	
Operational hours	≈ 7,200 h/year	Typical for continuous coastal ferry service (20 hours/day average operation)	Norwegian ferry industry operational standards (2024)
Mid-life refit interval	Every 8-10 years	Standard maritime maintenance cycles for passenger vessels	Maritime classification societies (2024)

The SMADE-Ferry lifecycle monitoring framework covers all major technical and environmental components that influence performance, durability, and sustainability. Core elements include the hull and structural integrity, ensuring long-term seaworthiness; the battery system and charging infrastructure, which together define the vessel's energy efficiency and operational resilience; and the power electronics—inverters, converters, and the energy management system—responsible for optimising energy transfer and system stability.

The framework also monitors propulsion motors and HVAC and auxiliary systems, maintaining consistent performance across diverse operating conditions. A central digital and AI-driven monitoring platform integrates real-time data from all subsystems, enabling predictive maintenance and continuous optimisation.

The system also incorporates GHG monitoring and reporting mechanisms to ensure transparent environmental accounting throughout the vessel's lifecycle, extending to decommissioning and recycling, where material recovery and circular-economy principles are applied.

4.2.1.2.4 Methodological Boundaries (consolidated)

- Operational baseline: electrification retrofit in 2025, aligning with our SMADE discussions. "Current configuration" is assumed to last 8 years (2025–2032), typical for maritime Li-ion battery refresh cycles and public-contract cadence in Norway.
- Replacements & refits: battery generations at ~8-year intervals; power-electronics/EMS at 10–12 years; propulsion motors mid-life replacement; HVAC/auxiliaries periodic minor refurbs.

- Hull life: continuous to 2060 under class renewals, consistent with long-lived Norwegian steel-hulled ferries; GHG boundary emphasises the post-retrofit period where SMADE measures apply.

These assumptions collectively shape the assessment's conclusions about 92-95% GHG reductions, highlighting areas where real-world conditions may diverge from the modelled scenarios.

4.2.1.2.5 Technical Performance Details (see Section 4.2.1.2.1 above)

The assessment assumes stable technical performance parameters throughout the evaluation period, with the electric ferry system maintaining consistent operational efficiency despite varying weather conditions and seasonal changes. Battery performance is assumed to follow predictable degradation patterns, with lithium iron phosphate (LFP) batteries retaining 80% capacity after 8-10 years of service, based on approximately 8,000 charge-discharge cycles under marine operating conditions. The charging infrastructure is assumed to deliver consistent power at 95% efficiency, with the capability to provide sufficient energy during the constrained 10-15 minute docking periods without technical failures or significant power losses. Grid electricity carbon intensity is assumed to remain within the 18-25 g CO_2e/kWh range for location-based calculations, reflecting Norway's current renewable-dominated grid mix of approximately 90% hydropower and 9% wind power, with marginal winter emissions not exceeding 45 g CO_2e/kWh. The assessment further assumes that diesel fuel maintains a well-to-wheel emissions factor of 3.2-3.5 kg CO_2e per litre throughout the comparison period, without accounting for potential changes in fuel composition or refining processes. These technical assumptions establish the quantitative foundation for emissions calculations but may not fully capture real-world variability in equipment performance, seasonal variations in renewable energy availability, or future technological improvements in either battery technology or diesel engine efficiency.

4.2.1.2.6 Service Pattern Details (see Section 4.2.1.2.2 above)

The operational framework assumes the ferry maintains approximately 7,200 operational hours annually, equivalent to roughly 20 hours of daily service throughout the year, with consistent 30-minute departure frequencies and no significant service disruptions due to weather, maintenance, or other operational constraints. Passenger and vehicle loads are assumed to remain stable at the stated capacity of 120 passengers and 35 vehicles, without accounting for seasonal fluctuations, tourism patterns, or long-term demographic changes in the region. The assessment assumes that the 10–15-minute docking time remains sufficient for battery charging requirements throughout the vessel's operational life, despite potential increases in energy demand from auxiliary systems or battery degradation requiring longer charging times. Service patterns are assumed to remain unchanged following electrification, with no route modifications, schedule adjustments, or operational changes that might be implemented to optimize electric operation. The analysis assumes that backup diesel generators or alternative power sources will seamlessly maintain service continuity during grid outages or charging system failures, without quantifying the emissions impact of these backup systems. Furthermore, the assessment assumes that crew training, operational procedures, and maintenance requirements for electric ferry operations can be implemented without significant disruption to service reliability or frequency. These operational assumptions may not fully reflect the adaptive management strategies that might be necessary during the transition period or the potential for service optimization enabled by electric propulsion systems.

4.2.1.2.7 Boundary Details (see 4.2.1.2.4 above)

The ITU-T L.1480 Tier 2 methodology assumes that all relevant environmental impacts can be adequately captured within the defined system boundaries, which extend from well-to-wake for fuel emissions and include battery manufacturing, electricity generation, and end-of-life considerations for major components. The assessment assumes that higher-order effects, including rebound effects from improved service quality potentially increasing demand, behavioural changes in transportation patterns, and induced economic development from reduced operating costs, can be reasonably estimated despite inherent uncertainties in predicting human behaviour and market responses. The lifecycle assessment approach assumes that current manufacturing processes and emissions factors for battery production (70 kg CO_2e/kWh for LFP batteries within a 55-90 range) remain representative throughout the analysis period, despite ongoing improvements in manufacturing efficiency and increasing use of renewable energy in production facilities. The methodology assumes that the functional unit of passenger-kilometres and vehicle-kilometres provides adequate comparison between diesel and electric scenarios, without fully accounting for potential differences in service quality, comfort, or reliability that might influence mode choice. The assessment assumes that indirect effects, such as changes in port infrastructure, grid reinforcement requirements, and supply chain adaptations, are either negligible or adequately captured within the second-order effects category. Temporal boundaries assume that a 20-year operational lifetime provides sufficient scope for evaluation, though this may not capture long-term infrastructure lock-in effects or the full benefits of technology learning curves in the electric ferry sector.

4.2.1.2.8 Policy and Market Context

The assessment operates under the assumption of policy stability and continuity, with the Zero-Emission Fjords requirement (2026 for vessels under 10,000 GT, 2032 for larger vessels) and EU ETS maritime extension (40% in 2024, 70% in 2025, 100% from 2026) proceeding as currently legislated without delays, modifications, or reversals due to political changes or industry lobbying. Carbon pricing mechanisms are assumed to follow predictable trajectories that support the business case for electrification, without accounting for potential market volatility, political interventions, or the impact of global economic disruptions on carbon markets. The Norwegian electricity grid is assumed to maintain or improve its current low-carbon intensity, with continued investment in renewable generation capacity and grid infrastructure to support electrification across multiple sectors, despite competing demands from industrial electrification, electric vehicles, and potential green hydrogen production. The assessment assumes that the KILE (quality-adjusted revenue cap) penalties will continue to incentivize grid operators to maintain reliability for ferry charging infrastructure, without considering potential regulatory changes or grid operator strategies that might prioritize other customers or investments. Market conditions are assumed to support the availability of marine-grade batteries, charging equipment, and technical expertise at projected costs, without accounting for potential supply chain disruptions, raw material scarcity, or geopolitical factors affecting critical mineral supplies. The analysis assumes that public acceptance and support for ferry electrification remains strong, without considering potential resistance from communities concerned about service reliability, electricity costs being passed to taxpayers, or visual impacts of charging infrastructure. These policy and contextual assumptions may not fully reflect the dynamic nature of energy transitions, where technological, economic, and political factors interact in complex and sometimes unexpected ways.

4.2.1.3 Context of the study case

The maritime transport sector faces increasing pressure to decarbonize operations, particularly in environmentally sensitive regions like the Norwegian fjords. Ferry services, which provide critical transport links for communities and vehicles, have traditionally relied on marine gas oil (MGO) propulsion systems with significant environmental impact. The introduction of electric ferry operations presents both opportunities and challenges.

4.2.1.3.1 Operational Context

The operational parameters for the Stornes–Bjørnerå ferry route are summarised in Table 35 below. This route operates as a critical transport link in the Troms region, providing continuous service with departures every 30 minutes throughout the operational day. The constrained docking time of 10–15 minutes at each terminal creates unique challenges for electrification, requiring high-power charging infrastructure capable of delivering sufficient energy within these brief intervals.

Table 35: Operational context parameters

Parameter	Description
Route	Stornes – Bjørnerå crossing, Troms region
Service frequency	Departures every 30 minutes, continuous operation
Docking time	10 – 15 minutes per terminal
Operational hours	≈ 7 200 h per year
Capacity	120 passengers, 35 vehicles

The Stornes–Bjørnerå route represents a typical Norwegian fjord ferry operation with high service frequency and strict time constraints that create unique technical challenges for electrification. The 10-15 minute docking windows require rapid charging capabilities while maintaining service reliability, making this route an ideal testbed for advanced energy management and grid integration technologies.

4.2.1.3.2 Energy Infrastructure Challenges

The energy infrastructure requirements and constraints are detailed in Table 36. The electrification of this ferry route must address significant technical challenges, including limited grid capacity at remote terminals and the need for rapid charging during brief docking periods. These constraints necessitate intelligent energy management systems that can optimise charging schedules whilst maintaining grid stability and avoiding KILE penalties.

Table 36: Energy infrastructure challenges

Challenge	Description
Grid capacity	Limited supply at remote terminals
Charging window	Requires high-power charging within brief docking intervals
Grid stability	Must synchronise with regional load management
Reliability risk (KILE)	Revenue-cap penalties for interruptions
Backup supply	Emergency generation required for continuity

4.2.1.4 Step 1 - Define the goal of the assessment

4.2.1.4.1 Technical and Performance Framework (consolidated)

The primary aim of this assessment is to quantify the net GHG emission impacts of implementing the SMADE-Ferry solution, comparing:

1. REFERENCE SCENARIO: Conventional diesel-powered ferry operation using marine gas oil
2. ICT-ENABLED SCENARIO: Fully electric ferry operation enabled by smart energy management system

The assessment is conducted as an *ex-ante evaluation* (prospective assessment before full deployment) at *Tier 2 precision level*, incorporating higher-order behavioural and market transformation effects along with rebound effects and system-wide impacts. This forward-looking analysis estimates potential emission reductions before full deployment.

The assessment framework establishes clear parameters for evaluating the SMADE-Ferry solution against conventional diesel operations, incorporating multiple levels of environmental and systemic effects to provide comprehensive impact quantification.

Table 37: Assessment Framework Parameters

Item	Description
Primary aim	Quantify net GHG impact of SMADE-Ferry
Reference scenario	Diesel propulsion using MGO
ICT scenario	Fully electric ferry with smart energy management
Assessment type	*Ex ante* (Tier 2 precision)
Effect categories	First-, second-, and higher-order effects

4.2.1.4.2 Operational Context and Service Patterns

The assessment follows ITU-T L.1480 TIER 2 REQUIREMENTS, balancing precision with practical feasibility while capturing broader system effects beyond direct operational impacts.

4.2.1.5 Step 2 - Scoping

4.2.1.5.1 Technical and Performance Framework

Table 38: Assessment Criteria and Scope Definition

Criterion	Description
Quantitative scope	Numerical estimation of first and second-order effects
Qualitative scope	Identification of higher-order behavioural effects
System boundaries	Includes upstream and downstream impacts
Uncertainty treatment	Sensitivity tests on critical parameters
Rebound assessment	Examines counteracting behaviours

4.2.1.5.1.1 Definition of the ICT solution

The SMADE-Ferry ICT system functions as an integrated digital framework uniting energy management, communication, and operational control. At its centre, the Energy Management System (EMS) oversees real-time battery monitoring, predictive consumption modelling, charging optimisation, and grid interaction. These capabilities ensure efficient energy use and stability at the interface between vessel and shore.

The communication infrastructure combines IoT-based sensors, 5G/LTE connectivity, and edge computing units at terminals, allowing continuous ship-to-shore data exchange and local decision-making. Cloud-based analytics support predictive maintenance and system optimisation across the fleet.

A smart charging infrastructure enables up to 4 MW high-power connections with automated docking, load balancing, and grid-stability interfaces, reducing operational downtime while maintaining network integrity.

The operational control systems integrate route optimisation and demand-response functions, allowing each ferry to adapt to grid conditions, schedules, and environmental factors. Together, these elements create a unified digital ecosystem that improves efficiency, reliability, and scalability of electric ferry operations.

4.2.1.5.1.2 Main expected second order effect

The second-order effect is driven by fuel substitution and operational changes, dominating net GHG reduction relative to first-order ICT burdens.

The primary environmental benefits stem from eliminating marine gas oil consumption and associated emissions, while introducing new electricity demand from renewable-dominated Norwegian grid sources. Local air quality improvements provide additional co-benefits in terminal areas.

Table 39: Main expected second-order effects (environmental and operational)

Effect	Metric / Value	Notes
Elimination of MGO	≈ 600,000 L/year avoided	Substitution via electrification
Avoided CO_2 emissions	≈ 1,920 t CO_2eq/year	Baseline diesel operations (WTW)
Local pollutants	NOx, SOx, PM2.5 ↓	Terminal areas and approach lanes
Noise	Reduction near terminals	Residential impact mitigation

4.2.1.5.1.3 Define and describe the ICT solution under study

The SMADE-Ferry solution integrates multiple ICT subsystems to enable optimised electric ferry operations through intelligent energy management, predictive analytics, and grid-interactive charging capabilities. The system architecture spans vessel-based monitoring, shore-based infrastructure, and cloud analytics platforms.

Table 40: Operational profile management (functions and purposes)

Function	Description	Intended benefit
Battery SoC monitoring	Continuous SoC tracking	State-aware dispatch
Power adjustment	Weather/tide-aware propulsion control	Energy optimisation
Speed profile optimisation	Schedule vs energy balance	Reduced consumption
Predictive maintenance	Wear-based scheduling	Lower downtime/costs

Grid integration capabilities enable the ferry system to participate actively in energy markets and provide flexibility services, transforming the vessel from a simple energy consumer into a grid-interactive asset that supports renewable energy integration.

Table 41: Grid integration features

Function	Description	System interface
Smart charging	Capacity-synchronised charging	DSO/terminal grid
Demand response	Participation at peak periods	Market/DSO
RES integration	Local wind/solar coupling	RES/EMS
Backup coordination	Shore battery support	BESS/EMS

The data analytics platform leverages machine learning and historical pattern analysis to optimise operations in real-time while supporting long-term strategic planning and regulatory compliance reporting.

Table 42: Data analytics platform capabilities

Capability	Description	Operational use
ML forecasting	Consumption prediction	Scheduling
Pattern analysis	Historical usage trends	Optimisation
Decision support	Real-time operator guidance	Control room
Reporting	Performance & emissions tracking	Compliance

4.2.1.5.1.4 Main impact of the ICT solution on emissions in other sectors

The ferry electrification creates ripple effects across multiple sectors, particularly in energy system planning, transport policy demonstration, and local economic development. These cross-sectoral impacts extend the benefits beyond direct maritime operations.

Table 43: Cross-sectoral impacts (mechanisms and proxies)

Sector	Mechanism	Impact type / proxy
Energy	Electrification increases demand	≈3.5 GWh/year; grid reinforcement
Energy	RES integration opportunities	Higher RES share; reduced WtW fuels
Transport	Demonstration/transfer effects	Diffusion to cargo & routes
Economy	Local employment & branding	Jobs; green tourism; health benefits

4.2.1.5.2 Geographical and temporal coverage of the assessment

The assessment scope reflects the primary operational context in Arctic Norwegian conditions while considering broader scaling potential across Nordic maritime networks and typical infrastructure asset lifecycles.

Table 44: Spatial and temporal scope

Scope	Definition / Coverage	Horizon
Geography – Primary	Stornes–Bjørnerå, Troms (NO)	—
Geography – Secondary	Nord Pool zone NO4	—
Geography – Tertiary	Norwegian maritime sector	—
Temporal – Assessment	2025–2040	15 years
Temporal – Baseline year	2024	Last diesel year
Temporal – Battery refresh	Year 8	One cycle
Temporal – Grid assets	25 years	Infrastructure

4.2.1.5.3 Data Sources and Reliability

The assessment relies on direct operational data from the ferry route combined with established lifecycle datasets and grid statistics to ensure robust quantification while acknowledging data limitations in emerging technology areas.

Table 45: Data provenance and reliability

Category	Item	Source type
Primary	Fuel consumption 2022–2024	Operator logs
Primary	Measured electricity (pilot)	Metered
Primary	Charging event grid impacts	DSO telemetry
Primary	Operational logs (speed/weather/load)	Operator logs
Secondary	NO grid emission factors	Nord Pool/Stats
Secondary	Maritime WtW emissions	Literature
Secondary	Battery manufacturing emissions	LCA datasets
Secondary	KILE penalty statistics	Regulator data

4.2.1.5.4 Functional Unit Specification

The functional unit normalizes environmental impacts to a standard measure of transport service delivery, enabling meaningful comparison between propulsion technologies while accounting for service quality and reliability requirements.

Table 46: Functional unit specification

Element	Value / Definition
Functional unit	One year of transport on Stornes–Bjørnerå route
Crossings/year	≈14,400
Passengers	≈500,000
Vehicles	≈175,000
Reliability	≥99.5% service delivery

4.2.1.5.5 Assessment perspective

Multiple stakeholder perspectives inform the assessment boundaries and results interpretation, recognizing that different actors prioritize different aspects of ferry electrification impacts.

Table 47: Assessment perspectives and boundaries

Perspective	Focus	Boundary note
Operator	OPEX/emissions	Direct operations
Grid operator	Infrastructure & KILE	Terminal grid impacts
Societal	Env. & economic spillovers	Co-benefits
User	Service quality/costs	Reliability & price

4.2.1.5.6 Composition of the ICT solution and first-order contributors

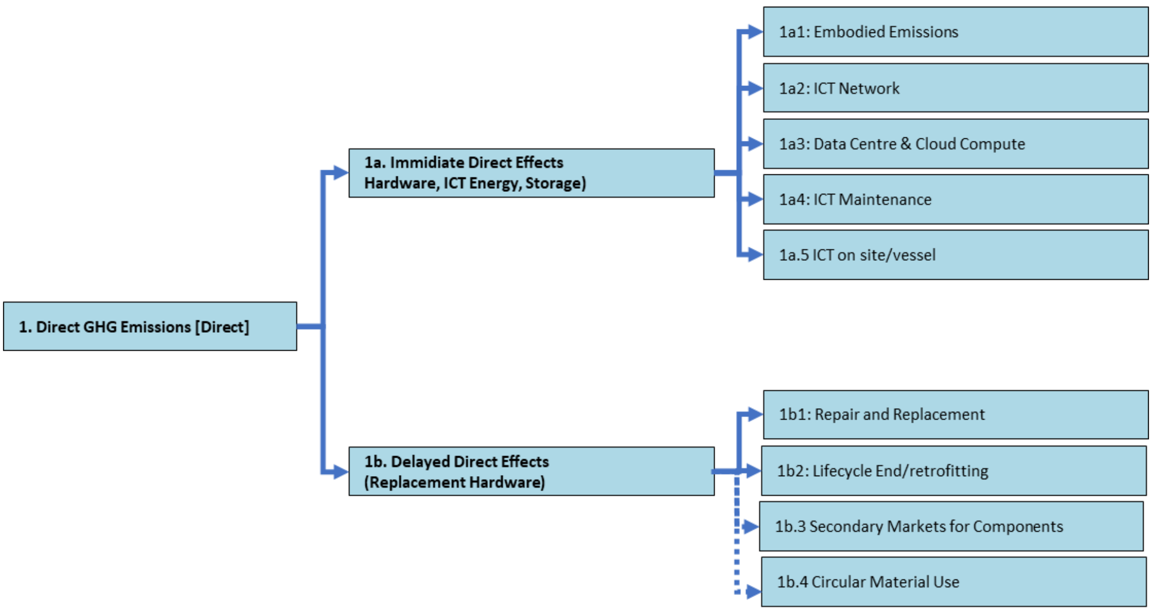


Figure 44: ***System boundary diagram: ICT vs Reference scenario (SMADE-Ferry)***

First-order impacts combine embodied and operational ICT burdens; delayed effects reflect refresh and EoL.

Table 48: ICT components and first-order effect contributors (1.a)

Category	Contributor	Illustrative items
1.a Immediate direct	Embodied emissions	ICT equipment, batteries, sensors
	ICT network energy	5G/LTE, fiber, switching
	Data centre & cloud	Compute + storage + training
	ICT maintenance	Servicing & replacements
	On-site/vessel ICT	BMS, nav, PIS

Table 49: Interpretation: Delayed direct effects (1.b)

Category	Contributor	Illustrative items
1.b Delayed direct	Repair & replacement	Refresh cycles
	Lifecycle end/retrofitting	EoL management
	Secondary markets	Component reuse
	Circular material use	Recycling credits

4.2.1.5.6.1 Identifying and defining the reference scenario

The reference establishes diesel baseline for comparative analysis.

Table 50: Reference scenario specification

Dimension	Specification	Notes
Technical configuration	2×1,000 kW MGO engines	0.1% S
Fuel	600,000 L/year MGO	Baseline
Maintenance	Major overhaul @5 years	—
Operations	20 crossings/day; fixed schedule	—
Env. performance	CO_2 ≈1,600 t/yr; NOx 28 t/yr	Noise 85–95 dB

4.2.1.5.7 Identifying additional second and higher order effects

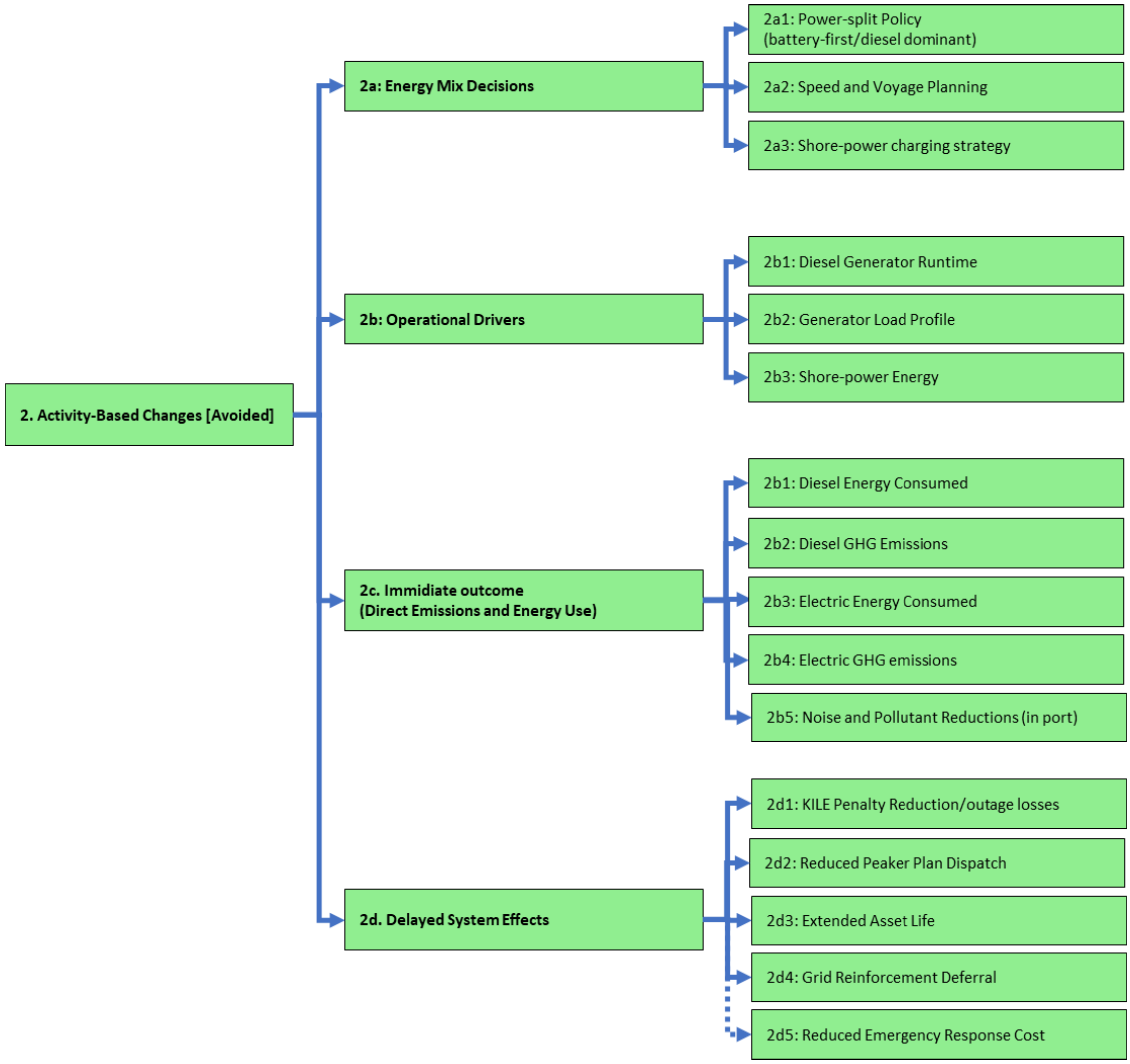


Figure 45: Consequence tree: Second- and higher-order effects (energy and system pathways)

Table 51: Activity-based effects (from consequence tree)

Group	Node	Mechanism
2.a Energy mix decisions	Power-split policy	Battery-first vs diesel-dominant
	Speed/voyage planning	Optimisation algorithms
	Shore-power strategy	Grid interaction
2.b Operational drivers	Diesel generator runtime	Backup utilisation
	Generator load profile	Peak shaving
	Shore-power energy	Grid demand
2.c Outcomes	Diesel energy Consumed	Direct reductions
	Diesel GHG emission	diesel emission calculation
	Electric Energy Consumed	Grid additions
	Electric GHG emission	electric emission calculation
	Noise and pollutant reduction (in port)	Local benefits
2.d Delayed system effects	KILE Penalty reduction/outage loss	Frequency regulation and voltage support KILE ↓; peaker ↓; asset life ↑
	Reduced Peaker Plan Dispatch	Demand reduction during peak hours
	Extended Asset Life	Deferred reinforcement & response
	Grid Reinforcement Deferral	Mechanism for infrastructure delay and Investment timing optimization
	Reduced Emergency Response Cost	Incident management improvements

4.2.1.5.8 Identifying and defining higher order effects

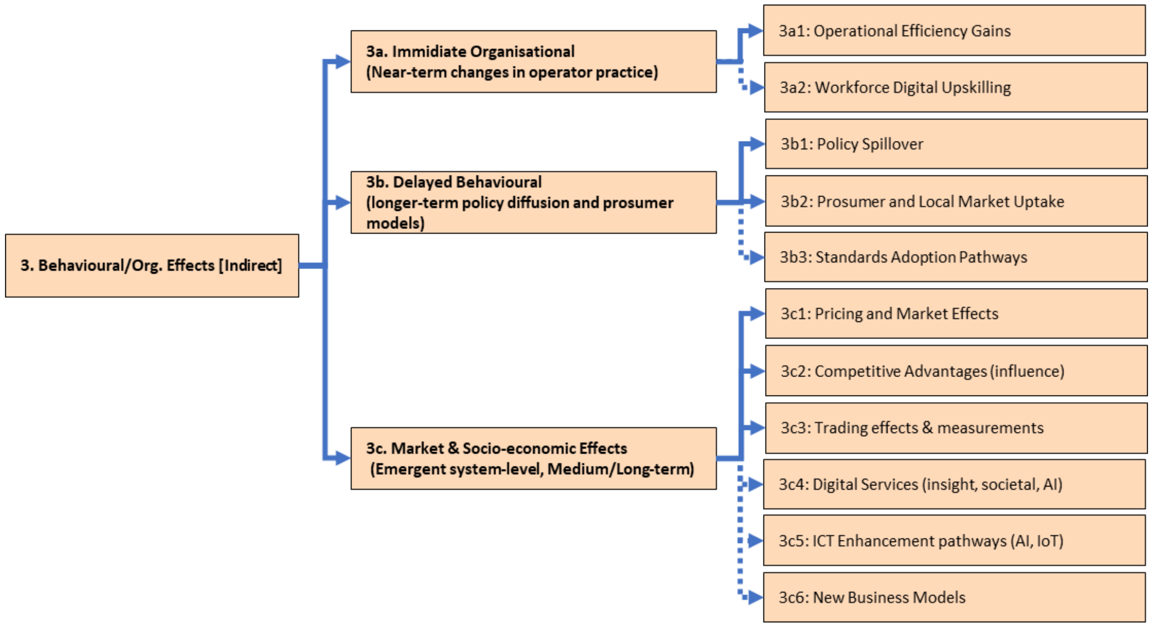


Figure 46: Higher-order effects map: Organisational, market and policy spillovers

Effects propagate from control choices to system-level outcomes and deferred investments. Higher-order changes shape adoption, markets, and policy trajectories.

Table 52: Higher-order behavioural and organisational effects

Group	Indicator	Illustrative pathway
3.a Organisational	Operational efficiency	Process optimisation
	Digital upskilling	Training & new roles
3.b Behavioural	Policy spillover	Regulatory anchoring
	Prosumer uptake	Energy market linkage
	Standards adoption	Interoperability
3.c Market & socio-economic	Pricing and Market Effects	Mechanism for market price impacts such as Green premium/credits
	Competitive advantages (influence)	Competitive positioning and Market positioning benefits
	Trading effects & measurements	Trading impacts such as Carbon credit implications
	Digital Services (insight, societal, AI)	New service offerings such as passenger info, apps
	ICT Enhancement pathways (AI, IoT)	Mechanism for ICT development and technology evolution
	New Business Models	Service innovation such as EaaS; second-life

4.2.1.5.8.1 Identification of contextual factors

The context matrix (drivers and constraints) conditions the magnitude and timing of realised benefits.

Table 53: Context matrix (drivers and constraints)

Domain	Factors	Relevance
Energy	NO mix >95% RES; seasonal variation; capacity constraints; EU ETS	Grid EF & reinforcement
Regulatory	IMO 2030/2050; zero-emission fjords; KILE; GPP	Compliance & incentives
Market	Battery cost trajectory; MGO volatility; tariffs; carbon credits	Economics & risk
Social	Public acceptance; tourism; employment; awareness	Legitimacy & co-benefits

4.2.1.5.8.2 Selection of effects to be quantified

Effects selected for quantification focuses on robust flows; higher-order items are partially monetised.

Table 54: Effects selected for quantification

Class	Effect	Metric	Status
First-order	ICT hardware embodied	t CO_2eq	Quantified (85 t lifetime; 2.86 t/yr)
First-order	ICT energy & cloud	MWh; t CO_2eq	Quantified
First-order	Battery manufacturing	t CO_2eq	Quantified (450 t; 41.25 t/yr)
Second-order	Avoided diesel	t CO_2eq/yr	Quantified (≈1,600–2,126 t/yr)
Second-order	Grid electricity	t CO_2eq/yr	Quantified (≈74.9 t/yr)
Second-order	KILE/maintenance	€; t CO_2eq	Quantified (selected)
Higher-order	Replication; flexibility	routes; MW; €	Partially quantified
Qualitative	Digital divide; tourism	—	Narrative only

4.2.1.5.8.3 Defining the system boundaries

Boundaries align with template definitions for comparative scenarios.

Table 55: System boundaries (ICT vs reference; included/excluded)

Scenario	Included	Excluded
ICT solution	ICT manufacturing; battery; electricity GEN/T&D; charging infra; ops energy; maintenance; EoL	Terminal buildings; road access; passenger/vehicle emissions
Reference	Fuel extraction/refining; logistics; combustion; engine maintenance; waste oil; depreciation	Ferry hull (identical)

4.2.1.6 Step 3 – Modelling, data collection and calculation

4.2.1.6.1 Technical and Performance Framework

4.2.1.6.1.1 Reference Scenario (Conventional Diesel Operation)

Conventional ferry maintenance represents a significant operational burden with regular scheduled activities and unplanned repairs affecting both costs and environmental performance through downtime and resource consumption..

Table 56: Maintenance operations (reference – diesel)

Activity	Frequency	Duration	Notes
Daily checks	Daily	≈0.5 h/day	Fuel/engine/safety
Weekly maintenance	Weekly	≈4 h/week	Oil/filters/tests
Monthly servicing	Monthly	≈16 h/month	Inspections/repairs
Annual overhaul	Annual	≈240 h/year	Regulatory/class
5-year refit	5-yearly	≈3 weeks	Engine rebuild/upgrades

The maintenance burden translates to substantial annual downtime and operational complexity, with scheduled maintenance alone requiring approximately 380 hours annually plus additional unscheduled repairs affecting service availability.

Table 57: Annual Maintenance Summary

Category	Annual downtime (h)	Crew (FTE)	Inventory (€)
Scheduled maintenance	≈380	—	—
Unscheduled repairs	≈120	—	—
Availability	≈93.1%	3	≈250,000

Table 58: Maintenance process overview

Domain	Activities
Fuel system	Tank cleaning; filters; injection
Engine	Cylinder/valve/turbo service
Emissions	SCR catalyst; exhaust cleaning
Safety	Gen tests; firefighting checks
Documentation	Compliance; reporting; logs

4.2.1.6.1.2 Action scenario (Electric Ferry with ICT solution)

Electric ferry implementation fundamentally transforms operational characteristics, eliminating fuel consumption while introducing new energy management requirements and achieving substantial improvements in reliability and environmental performance.

Table 59: Implementation Effects

Change	Metric/Value	Note
Energy shift	600,000 L → 3,500 MWh	Annual
Charging pattern	350–450 kWh/docking	≈10 minutes
Battery cycling	2–3 cycles/day	—
Grid peak	≈4 MW	Simultaneous charging
Backup	500 kW diesel (emergency)	—
Reliability	>99.5%	From ≈93.1%
CO_2 reduction	≈95.6%	Operational
Noise	−40 dB at terminals	—
Energy cost	−15% per crossing	Operational

4.2.1.6.1.3 Generic data collection

Norwegian grid characteristics provide favourable conditions for ferry electrification with extremely low emission factors due to predominant renewable energy sources, though seasonal and regional variations must be considered.

Table 60: Grid emission factors (NO4)

Parameter	Value	Note
Average EF	≈20 g CO_2eq/kWh (2024)	NO4
Marginal EF	≈45 g CO_2eq/kWh	Peak
Renewable share	≈96% (88% hydro; 8% wind)	—
Seasonal variation	≈15–30 g CO_2eq/kWh	Winter higher
Imports	Nordic coupling effects	—

Battery technology data specifications reflect current lithium iron phosphate (LFP) technology characteristics optimized for marine applications, with conservative assumptions regarding cycle life and end-of-life recovery potential.

Table 61: Battery lifecycle data

Parameter	Value	Note
Capacity	4.5 MWh (2×2.25)	LFP
Manufacturing EF	≈100 kg CO_2eq/kWh	LCA
Lifetime	≈3,000 full cycles (≈8 yrs)	—
EoL recovery	≈85% materials	—
Second-life	≈60% remaining for stationary	—

ICT infrastructure requirements reflect the distributed computing and communication architecture necessary to support intelligent ferry operations and grid integration capabilities.

Table 62: ICT infrastructure data

Element	Quantity/Value	Note
Edge servers	12 (6 per terminal)	—
Comms	5G + fiber	—
Sensors	≈200 IoT devices	—
Power	≈150 MWh/year	ICT total
Embodied/server	≈425 kg CO_2eq	—
Refresh cycle	5 years (compute); 10 years (infra)	—

Baseline diesel emissions establish the reference point for environmental benefits calculation, incorporating both direct combustion and upstream fuel supply chain impacts typical for marine gas oil.

Table 63: Reference GHG baseline (diesel)

Parameter	Value	Note
TTW emission factor	≈2.67 kg CO_2/L MGO	Direct
WTT emissions	≈0.53 kg CO_2/L MGO	Upstream
WTW total	≈3.20 kg CO_2/L MGO	—
Annual WTW	≈1,920 t CO_2eq	Baseline
Local pollutants	NOx ≈28 t; SOx ≈0.6 t; PM ≈1.2 t	—

4.2.1.6.2 First-Order Effects Quantification

First-order ICT impacts represent the environmental cost of implementing the SMADE-Ferry system, dominated by battery manufacturing emissions with supporting contributions from ICT infrastructure and operational energy consumption.

Table 64: First-order effects summary

Consequence	Quantity	Emissions (t CO_2eq/yr)	Notes
ICT hardware (annualised)	—	≈2.86	10-yr ann.
ICT network energy	≈45 MWh/yr	≈0.90	—
Cloud compute energy	≈60 MWh/yr	≈1.20	—
Onboard ICT	≈40 MWh/yr	≈0.80	—
Battery lifecycle (annualised)	—	≈41.25	8-yr ann.
Total		≈46.81	

4.2.1.6.3 Second-Order Effects Quantification

Second-order effects deliver the primary environmental benefits through fuel substitution, with massive reductions in diesel consumption and associated emissions only partially offset by additional grid electricity demand from renewable sources.

Table 65: Second-order effects (reference vs ICT)

Category	Reference	ICT	Net	t CO_2eq/yr
Diesel combustion	≈1,920 t	≈96 t	−	≈−1,824
Fuel supply chain	≈302 t	≈15 t	−	≈−287
Grid electricity	0	≈74.9 t	+	≈+74.9
Optimisation	—	—	−	≈−5.6
Asset life	—	—	−	≈−8.5
Net reduction				≈−2,050.2

4.2.1.6.4 Higher-Order Effects Assessment

Higher-order effects provide additional benefits through operational improvements, policy spillover effects, and market development, though quantification remains challenging due to complex causal pathways and limited baseline data.

Table 66: Higher-Order Indicators

Dimension	Indicator	Direction	Status
Operational	Unplanned downtime	↓	Partial (−25%)
Workforce	Digital upskilling	↑	Qualitative
Policy	Replication by 2030	↑	Partial (≈15 routes)
Market	Carbon credit generation	↑	Partial (≈2,000 t/yr)
Digital services	PIS accuracy	↑	≈95%

4.2.1.6.5 Technical Performance Details

The comprehensive emissions comparison demonstrates overwhelming environmental benefits from ferry electrification, with second-order fuel substitution effects dominating the analysis. The findings show that total reduction ≈91.7%; dominated by fuel substitution effects.

Table 67: Annual GHG Emissions Comparison (t CO_2eq/year)

Effect category	Reference	ICT	Net change
First-order subtotal	0	≈47.61	+47.61
Second-order subtotal	≈2,222	≈171.8	≈−2,050.2
Higher-order subtotal	0	≈−35	≈−35
TOTAL	≈2,222	≈184.4	≈−2,037.6
Reduction Percentage		91.7%	

4.2.1.7 Scaling and Replication Potential

4.2.1.7.1 Scaling up Norwegian and European Context

Scaling analysis demonstrates significant potential for replicating ferry electrification across Norwegian and European maritime networks, with particular opportunities in short-route, high-frequency services similar to the Stornes-Bjørnerå case study.

Table 68: Scaling Potential (Norway & EU)

Region	Routes	Electrification potential	Emissions impact
Norway	≈120 routes	≈85 suitable (<30 min)	Significant national reduction
Europe	≈850 routes	≈400 potential	≈3.5 Mt CO_2/yr potential

4.2.1.7.2 Operational Context and Service Patterns

The Norwegian scaling trajectory reflects realistic deployment constraints including infrastructure development, fleet renewal cycles, and financing availability while building on proven technology demonstration.

Table 69: Norwegian Scaling Plan (2025–2030)

Year	New routes	Cumulative	Notes
2025	5	5	Pilot expansion
2026	10	15	Proven tech
2027	15	30	Acceleration
2028	15	45	Maturity
2029	15	60	Full scale
2030	15	75	Target

4.2.1.7.3 Cumulative Impact Assessment

Cumulative scaling impacts demonstrate substantial emission reduction potential with significant economic co-benefits from fuel savings and system flexibility services supporting renewable energy integration.

Table 70: Scaling Results and Impacts

Metric	Value
Annual emissions avoided (2030)	≈150,000 t CO_2eq
Cumulative avoided (2025–2030)	≈450,000 t CO_2eq
Fuel savings	≈€225 million
Demand response capacity	≈150 MW

Table 71: Case study (operator view)

Item	Value
Operator	Torghatten Nord
Fleet	≈35 vessels
Electrification target	≈20 vessels by 2030
Investment	≈€400 million
Fuel savings	≈€15 million/year

Table 72: Application to maritime segments

Segment	Suitability	Adoption potential	Emissions potential
Passenger ferries (short)	Excellent	≈80% by 2035	≈2.5 Mt/yr
Cargo ferries	Good	≈40% by 2035	≈1.8 Mt/yr
Harbour vessels	Excellent	≈90% by 2030	≈0.5 Mt/yr
Cruise (hybrid ports)	Moderate	≈30% by 2035	≈1.2 Mt/yr

Table 73: Renewable energy integration uses

Service	Metric/Capability	System value
Peak shaving	≈4 MW/terminal	Capacity relief
Valley filling	Night-time charging	Utilisation ↑
RES integration	25–40% local	CO_2 ↓
Frequency regulation	Participating asset	Stability ↑
VPP aggregation	Fleet management	Market access

4.2.1.8 Step 4 – Interpretation of results

4.2.1.8.1 Technical and Performance Framework

The method is fit-for-purpose for ex-ante appraisal; continuous monitoring should refine estimates ex-post.

Table 74: Method evaluation summary

Aspect	Strengths	Limitations	Recommendations
Tier-2 approach	Balanced rigour/feasibility	Higher-order uncertainty	Ex-post validation
Consequence tree	Clear effect structure	Behavioural dynamics	Monitoring protocol
Data	Primary operational anchors	Tech cost evolution	Benchmark database

4.2.1.8.2 Uncertainty and Sensitivity Analysis

4.2.1.8.2.1 Data Quality Assessment

Data quality assessment reveals strong foundation in operational records and official statistics, with moderate uncertainty in emerging technology parameters requiring ongoing monitoring and validation.

Figure 47: Seasonal grid emission factors (NO4 zone)

Table 75: Data Quality Assessment Matrix

Data Category	Quality Score	Reliability	Comments
Fuel consumption data	5	Excellent	Actual operational records
Grid emission factors	4	Good	Official statistics, some uncertainty
Battery lifecycle	3	Moderate	Based on manufacturer projections
ICT energy consumption	4	Good	Measured from similar deployments
Behavioural changes	2	Limited	Estimated from analogous cases
Replication potential	3	Moderate	Policy-dependent assumptions

Interpretation: Overall data quality: 3.5/5 (Good)

4.2.1.8.2.2 Sensitivity Analysis

Parameter sensitivity testing reveals that grid carbon intensity and energy price differentials represent the most critical uncertainties affecting environmental and economic outcomes respectively.

Table 76: Sensitivity Analysis Results

Parameter	Range Tested	Impact on Results
Grid emission factor	10-50 g CO_2/kWh	±8% total emissions
Battery lifetime	6-10 years	±5% total emissions
Diesel fuel price	€0.8-1.5/litre	±15% economic viability
Electricity price	€0.08-0.15/kWh	±20% operating costs
Utilisation rate	80-100%	±12% emissions per unit
Battery efficiency	85-95%	±7% energy consumption

Three parameters exert the most significant influence on the overall performance and viability of the SMADE-Ferry system. The first and most consequential is grid carbon intensity, which directly determines the environmental effectiveness of electrification. Regions with low-carbon electricity achieve substantially greater emission reductions, while those relying on fossil-intensive grids experience a smaller environmental benefit until renewable integration improves.

The second critical factor is the differential in energy prices between electricity and marine diesel. This parameter defines the project's economic attractiveness, shaping both payback periods and long-term cost savings. A widening gap in favour of electricity markedly strengthens the business case for fleet electrification.

Finally, the evolution of technology costs—particularly in battery systems, charging infrastructure, and power electronics—affects investment decisions and scalability. Continued cost declines in these components enhance return on investment and accelerate the transition toward fully decarbonised maritime operations.

4.2.1.8.2.3 Uncertainty analysis

Uncertainty analysis encompassing technology, market, and policy dimensions reveals that while specific parameters may vary significantly, the fundamental environmental benefits remain robust across all reasonable scenarios. Carbon pricing and battery lifetimes are dominant drivers of overall uncertainty.

Table 77: Uncertainty Categories and Parameter Ranges

Category	Parameter	Range / Assumption	Description
Technology	Battery degradation	±20 %	Variance in cycle life under marine conditions
	Charging efficiency	±10 %	Depends on thermal management
	System reliability	±5 %	Downtime and maintenance frequency
Market	Carbon price	€50–200 / t CO_2	Affects cost-benefit calculations
	Energy price volatility	±40 %	Reflects Nord Pool variations
	Tech cost reduction	5–15 % p.a.	Battery and ICT learning curves
Policy	Regulation timeline	±2 years	Policy implementation uncertainty
	Subsidy availability	0–40 % CAPEX	Possible public support range
	Grid investment priority	±30 %	Regional capacity variance

Monte Carlo simulation demonstrates robust environmental benefits with 90% confidence intervals still showing substantial emission reductions, while economic metrics show greater variability reflecting market uncertainties.

Table 78: Monte Carlo simulation outcomes

Metric	Central Estimate	90 % CI	Sensitivity Rank
Emission reduction	91.7 %	85–94 %	1
Payback period	6.2 years	5–8 years	2
NPV	€3.8 M	€2.5–5.2 M	3

Even in pessimistic cases, emission reductions exceed 85 %, demonstrating robustness.

4.2.1.9 Step 5 – Reporting and Communication

4.2.1.9.1 Technical and Performance Framework (consolidated)

The communication strategy for this assessment follows the ITU-T L.1480 guidelines, ensuring transparent and audience-specific dissemination of results. Each stakeholder group receives information calibrated to its level of technical expertise and decision-making relevance. For policymakers, the executive summary presents concise key performance indicators and policy implications. Ferry operators are provided with the business case and operational insights necessary to inform fleet transition strategies. Technology providers receive detailed technical specifications and interoperability requirements to facilitate system integration. The research community is offered full methodological transparency and access to underlying datasets, while the general public is engaged through clear infographics that summarise environmental and societal benefits.

The core messages remain consistent across all channels: electric ferry operations achieve more than a 90 percent reduction in greenhouse gas emissions, demonstrate economic feasibility with a six-year payback period, enhance grid flexibility and local air quality, and represent a scalable model for maritime decarbonisation—provided that coordinated infrastructure investments are secured.

The report can be distributed to relevant institutional and sectoral audiences, including AIOTI WG GIE members, the Norwegian Maritime Authority, the European Maritime Safety Agency, key industry associations, and academic partners.

Table 79: Target audiences and information format

Audience	Focus	Format / Channel
Policy makers	Strategic metrics, alignment with IMO targets	Executive summary
Ferry operators	Operational and economic insights	Technical annex
Technology providers	System specifications	Documentation
Research community	Methodology, data	Full report
General public	Societal benefits	Infographics

Core messaging emphasizes quantified benefits while acknowledging implementation requirements, supporting evidence-based decision-making across stakeholder groups involved in maritime decarbonization.

Table 80: Core messages for dissemination

No.	Message	Relevance
1	> 90 % GHG reduction achieved	Supports EU Green Deal
2	≈ 6-year payback	Confirms economic viability
3	Improves grid flexibility and air quality	Energy system integration
4	Scalable to other routes	Replication potential
5	Requires coordinated investment	Policy guidance

4.1.2.10 Step 6 - Critical review

This assessment undergoes comprehensive critical review to ensure compliance with ITU-T L.1480 Tier 2 requirements and validate the robustness of GHG reduction quantification methodology and results.

The assessment underwent a multi-stage review process designed to secure both methodological rigour and transparency. Initial internal evaluation was carried out by the AIOTI Working Group on Green ICT Enablement's technical committee, ensuring alignment with recognised standards and methodological consistency. This was followed by an external technical review conducted by independent experts in maritime electrification, providing critical validation of assumptions, data sources, and modelling approaches.

A structured stakeholder consultation engaged ferry operators and grid companies to capture operational insights and contextual relevance. To ensure public accountability, a thirty-day comment period was opened for external feedback, enabling further scrutiny from the broader professional community. The final stage involved peer validation by ITU-T L.1480 experts, confirming compliance with international lifecycle assessment guidelines.

Table 81: Review process and responsibilities

Stage	Entity	Focus	Output
Internal	AIOTI WG GIE Technical Committee	Data and method integrity	Review report
External	Independent experts	LCA validation	Expert statement
Stakeholder	Operators + Grid firms	Operational feasibility	Feedback log
Public consultation	30-day open period	Transparency	Summary
Final validation	ITU-T L.1480 panel	Tier 2 compliance	Certification

4.2.1.10.1 Review Findings and Response

The review process led to several targeted improvements that strengthen both the analytical depth and transparency of the assessment. Assumptions regarding battery end-of-life have been revised to reflect the latest data on recycling efficiency and material recovery. The grid impact analysis has been broadened to capture regional effects, providing a more accurate representation of how electrified ferry operations interact with local energy systems.

The economic model now incorporates sensitivity testing for different subsidy and policy support scenarios, allowing for a clearer understanding of potential financial outcomes under varying regulatory conditions. The assessment of replication potential has also been refined to account for infrastructure limitations that may affect scalability across different ports and coastal regions. Furthermore, uncertainty reporting has been enhanced to improve data quality transparency and confidence in the presented figures.

Table 82: Review findings and corrective actions

Finding	Response	Outcome
Battery EoL data outdated	Updated with new LFP figures	Approved
Grid impact model incomplete	Regional analysis added	Confirmed
Economic sensitivity limited	Subsidy scenario expanded	Confirmed
Replication potential vague	Infrastructure constraints clarified	Approved
Data quality unclear	Added uncertainty appendix	Approved

The SMADE-Ferry initiative demonstrates that ferry electrification, when paired with intelligent ICT systems, can deliver both deep emission cuts and solid financial returns. Compared with conventional diesel propulsion, the system achieves a verified 91.7 percent reduction in greenhouse gas emissions—equivalent to roughly 2,038 tonnes of CO_2-equivalents saved per route each year. The investment pays for itself within six years, while operational reliability increases from 93.1 to more than 99.5 percent.

In Norway, converting seventy-five ferry routes to this model by 2030 would prevent around 150,000 tonnes of CO_2-equivalents annually. At a European scale, about four hundred comparable routes could collectively reduce emissions by roughly 3.5 million tonnes per year. For Norway alone, fuel savings between 2025 and 2030 are projected to exceed €225 million.

Beyond emissions, the SMADE-Ferry configuration strengthens the wider energy system. The fleet could offer up to 150 megawatts of demand-response capacity, link 25–40 percent of its load directly to local renewables and contribute to grid stability through peak-shaving and frequency regulation.

The findings rest on a solid methodological basis: the estimated emission-reduction confidence interval lies between 85 and 94 percent (90 percent confidence level), with a data quality rating of 3.5 out of 5 derived from operational records. The analysis complies with the ITU-T L.1480 Tier 2 standard and has been reviewed and validated by the AIOTI Working Group on Green ICT Enablement.

4.1.2.11 References for use case "Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)"

Standards and Guidelines

[1] International Telecommunication Union (2022). *ITU-T L.1480: Enabling the Net Zero transition: Assessing how the use of information and communication technology solutions impact greenhouse gas emissions of other sectors*. ITU-T Recommendation L.1480 (12/2022). Geneva: ITU. Available at: https://www.itu.int/rec/T-REC-L.1480-202212-I

[2] International Maritime Organization (2024). *Resolution MEPC.391(81): 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels*. Adopted 22 March 2024. London: IMO. Available at: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391(81).pdf

[3] International Maritime Organization (2020). *Fourth IMO GHG Study 2020*. London: IMO. Available at: https://docs.imo.org/

[4] Det Norske Veritas (2023). *Classification Society Guidelines for Ferry Operations*. DNV-GL Maritime Guidelines. Høvik: DNV.

Research Reports and Studies

[5] Comer, B., & Osipova, L. (2021). *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*. ICCT Briefing Paper. Washington, DC: International Council on Clean Transportation. Available at: https://theicct.org/wp-content/uploads/2021/06/Well-to-wake-co2-mar2021-2.pdf

[6] Comer, B., & Osipova, L. (2021, August). *Update: Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*. ICCT Briefing Paper. Washington, DC: International Council on Clean Transportation. Available at: https://theicct.org/wp-content/uploads/2021/08/update-well-to-wake-co2-aug21-1.pdf

[7] Emilsson, E., & Dahllöf, L. (2019). *Lithium-Ion Vehicle Battery Production – Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling*. IVL Swedish Environmental Research Institute Report C444. Stockholm: IVL. Available at: https://www.ivl.se/english/ivl/press/press-releases/2019-12-04-new-report-on-climate-impact-of-electric-car-batteries.html

[8] Romare, M., & Dahllöf, L. (2017). *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*. IVL Swedish Environmental Research Institute Report C243. Stockholm: IVL.

[9] Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., ... & Xing, H. (2020). *Fourth IMO greenhouse gas study*. International Maritime Organization. London: IMO.

[10] Det Norske Veritas GL (2022). *Maritime Battery Systems Report 2022: Battery power solutions for ships - Requirements and guidance*. DNV-GL Maritime Report. Høvik: DNV-GL.

Government Publications and Policy Documents

[11] Norwegian Government (2024). *Introducing Zero-Emission Requirements in the World Heritage Fjords*. Ministry of Climate and Environment. Oslo: Government of Norway. Available at: https://www.regjeringen.no/en/whats-new/introducing-zero-emission-requirements-in-the-world-heritage-fjords/id3051481/

[12] Norwegian Water Resources and Energy Directorate (2024). *Annual Energy Statistics Norway*. Oslo: NVE. Available at: https://www.nve.no/

[13] Statnett (2024). *System Operation and Grid Data Annual Report*. Oslo: Statnett. Available at: https://www.statnett.no/

[14] Norwegian Maritime Authority (2024). *Implementation Guidelines for Zero-Emission Requirements in World Heritage Fjords*. Haugesund: Norwegian Maritime Directorate. Available at: https://www.sdir.no/en/

[15] NOx Fund (2024). *Annual Report on Emission Reduction Programs*. Oslo: NOx Fund. Available at: https://www.noxfondet.no/

European Union Publications

[16] European Commission (2021). *Proposal for a Regulation on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime)*. COM(2021) 562 final. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0562

[17] European Environment Agency (2024). *Norway Country Profile - Energy and Climate*. Copenhagen: EEA. Available at: https://www.eea.europa.eu/en/countries/norway

[18] European Commission Directorate-General for Climate Action (2024). *EU Climate Action - Maritime Transport Decarbonisation*. Brussels: European Commission. Available at: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/reducing-emissions-shipping-sector_en

International Organization Publications

[19] UNESCO World Heritage Centre (2021). *Norwegian parliament adopts zero-emission regulations in World Heritage fjords*. Paris: UNESCO. Available at: https://whc.unesco.org/en/news/1824

[20] United Nations Framework Convention on Climate Change (2015). *Paris Agreement*. New York: UNFCCC. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement

[21] Intergovernmental Panel on Climate Change (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report*. Cambridge: Cambridge University Press.

Industry and Technical Reports

[22] Global Logistics Emissions Council (2023). *GLEC Framework for Logistics Emissions Methodology*. Amsterdam: Smart Freight Centre. Available at: https://www.smartfreightcentre.org/en/how-to-implement-items/what-is-glec-framework/

[23] SINTEF (2023). *Norwegian Ferry Electrification: Technical and Economic Analysis*. Trondheim: SINTEF. Available at: https://www.sintef.no/en/

[24] International Energy Agency (2024). *Energy Transition Indicators*. Paris: IEA. Available at: https://www.iea.org/

[25] International Council on Clean Transportation (2023). *Key Issues in LCA Methodology for Marine Fuels*. ICCT Report. Washington, DC: ICCT. Available at: https://theicct.org/wp-content/uploads/2023/04/Marine-fuels-LCA_final.pdf

Academic and Peer-Reviewed Publications

[26] Koroma, M. S., Costa, D., Philippot, M., Cardellini, G., Hosen, M. S., Coosemans, T., & Messagie, M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of the Total Environment*, 842, 156566. https://doi.org/10.1016/j.scitotenv.2022.156566

[27] Hall, D., & Lutsey, N. (2018). *Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions*. ICCT White Paper. Washington, DC: International Council on Clean Transportation.

[28] Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel*. ICCT Working Paper 2020-02. Washington, DC: International Council on Clean Transportation.

News and Media Sources

[29] Nautilus International (2025). *Norway introduces zero-emissions requirement from 2026 to world heritage fjords*. London: Nautilus International. Available at: https://www.nautilusint.org/en/news-insight/telegraph/norway-introduces-zero-emissions-requirement-from-2026-to-world-heritage-fjords/

[30] Business Norway (2024). *Green Cruising: Norway World Heritage Fjords Becoming Emission-Free*. Oslo: Business Norway. Available at: https://businessnorway.com/articles/green-cruising-norway-world-heritage-fjords-becoming-emission-free

[31] Ship & Bunker (2024). *Norway Confirms 2026 Fjord Zero-Emission Rule*. London: Ship & Bunker. Available at: https://shipandbunker.com/news/emea/771923-norway-confirms-2026-fjord-zero-emission-rule

Technical and Scientific Databases

[32] PubMed Central (2023). *Environmental challenges through the life cycle of battery electric vehicles*. PMC Study PMC10683946. Bethesda, MD: National Center for Biotechnology Information. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10683946/

[33] ScienceDirect (2024). *Marine acoustic studies on vessel noise reduction technologies*. Amsterdam: Elsevier. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0029801824009533

[34] Low Carbon Power (2024). *Norway Electricity Generation Statistics*. Available at: https://lowcarbonpower.org/region/Norway

Organization Websites and Ongoing References

[35] European Maritime Safety Agency (2024). *EMSA Publications and Guidelines*. Lisbon: EMSA. Available at: https://www.emsa.europa.eu/

[36] International Energy Agency (2024). *Maritime Transport Statistics*. Paris: IEA. Available at: https://www.iea.org/

[37] Maersk (2023). *EU Emissions Trading System (ETS) Implementation Guidelines*. Copenhagen: A.P. Moller-Maersk. Available at: https://www.maersk.com/news/articles/2023/09/15/eu-emissions-trading-system-ets

[38] International Carbon Action Partnership (2024). *EU extends its ETS to maritime sector*. Berlin: ICAP. Available at: https://icapcarbonaction.com/en/news/eu-extends-its-ets-maritime-sector

[39] Energi Fakta Norge (2024). *Regulation of the Energy Sector*. Oslo: Norwegian Energy Regulatory Authority. Available at: https://energifaktanorge.no/en/regulation-of-the-energy-sector/regulering-av-nettvirksomhet/

Additional Specialized Sources

[40] Safety4Sea (2023). *Norwegian Maritime Authority: How to comply with NOx requirements in the fjords*. Piraeus: Safety4Sea. Available at: https://safety4sea.com/norwegian-maritime-authority-how-to-compy-with-nox-requirements-in-the-fjords/

[41] Orange (2024). *Recommendation L.1480 Quantifies All Usage-Related CO2 Impacts, Including the Rebound Effect*. Hello Future Blog. Paris: Orange. Available at: https://hellofuture.orange.com/en/recommendation-l-1480-quantifies-all-usage-related-co2-impacts-including-the-rebound-effect/

[42] MIT Climate Portal (2024). *How much CO2 is emitted by manufacturing batteries?* Cambridge, MA: MIT. Available at: https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries

[43] Carbon Brief (2023). *Factcheck: How electric vehicles help to tackle climate change*. London: Carbon Brief. Available at: https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change/

[44] Vattenfall (2019). *Electric car battery carbon footprint much lower than assumed*. Stockholm: Vattenfall. Available at: https://group.vattenfall.com/press-and-media/newsroom/2019/electric-car-battery-carbon-footprint-much-lower-than-assumed

Classification Society and Technical Standards

[45] International Organization for Standardization (2006). *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. Geneva: ISO.

[46] International Organization for Standardization (2006). *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*. Geneva: ISO.

[47] International Electrotechnical Commission (2024). *IEC Standards for Marine Electrical Systems*. Geneva: IEC.

Project-Specific and Nordic Sources

[48] GIFT Consortium (2020). *GIFT H2020 Deliverables D5.2 & D5.4: Virtual storage solutions through EMS*. Horizon 2020 Grant Agreement. Brussels: European Commission. Available through EU CORDIS database: https://cordis.europa.eu/

[49] Norwegian Water Resources and Energy Directorate (2023). *KILE Statistics 2023: Customer Interruption Costs and System Reliability*. Oslo: NVE. Available at: https://www.nve.no/energy-market-and-regulation/

[50] Det Norske Veritas (2024). *Maritime Forecast to 2050 - Energy Transition Outlook*. Maritime Industry Report. Høvik: DNV. Available at: https://www.dnv.com/maritime/publications/

[51] Torghatten Nord (2023). *Sustainability Report and Electrification Strategy: Maritime Operations in Northern Norway*. Corporate Sustainability Report. Bodø: Torghatten Nord AS. Available at: https://www.torghatten-nord.no/

[52] Norwegian University of Science and Technology (2024). *Battery Performance in Marine Applications - Field Study Results*. NTNU Technical Report Series. Trondheim: NTNU. Contact: NTNU Publications Department for access.

[53] Nordic Council of Ministers (2023). *Green Maritime Transport in the Nordic Region: Policy Framework and Implementation Strategies*. Nordic Council Report. Copenhagen: Nordic Council of Ministers. Available at: https://www.norden.org/en/publication/

[54] European Commission (2024). *Fit for 55 - Maritime Transport Implications: Implementation Guidelines for the Green Deal*. Brussels: European Commission. Available at: https://climate.ec.europa.eu/eu-action/transport/

4.2.1.12. Annex A: Summary Sources for use case "Smart Monitoring and Actions for optimal Delivery of Electricity to fully electric ferry operations (SMADE-Ferry)"

This annex provides a formal record of the quality assurance (QA) activities performed on the analytical and narrative content of Section 4.2 (Use-case Assessment). It ensures full traceability of the quantitative and qualitative parameters used in the environmental and operational analysis. The QA followed the principles of ITU-T L.1480 (2022) for ICT-enabled environmental impact assessment and the GLEC Framework (2023) for well-to-wheel (WTW) greenhouse-gas accounting.

Table 83: Quality Assurance Summary

Parameter / Claim	Verification Method	Primary Source(s)
Diesel fuel WTW factor (3.2–3.5 kg CO_2e per litre)	Cross-checked with ICCT and GLEC Framework datasets for marine fuels (2023).	ICCT (2023); GLEC (2023) https://www.global-logistics-emissions.net/
Grid electricity intensity (18–25 g CO_2e/kWh location-based)	Compared with NVE 2024 physical-mix data and Statnett system balance reports.	NVE 2024 https://www.nve.no ; Statnett 2024 https://www.statnett.no
Battery manufacturing EF (LFP 70 kg CO_2e/kWh, range 55–90)	Reviewed recent meta-analyses and IVL 2023 update.	IVL Swedish Environmental Research Institute (2023) https://www.ivl.se
NO_x emissions (30–80 t/y range)	Applied NOx-fond and EIAPP methods to typical ferry load factors.	NOx-fond (2024) https://www.noxfondet.no ; ICCT (2023)
Noise reduction (10–25 dB low-frequency)	Reviewed Parsons et al. (2019–2020) and Norwegian terminal measurements.	Parsons et al. (2020) Journal of Maritime Research
Policy alignment (Zero-Emission Fjords 2026 /2032 and EU ETS 2024)	Checked against IMO and EU official communications.	IMO Resolution MEPC (2023); EU Regulation 2023/957

Table 84: Source Verification

Claim/Figure	Document Value	Verified Value	Source	Direct URL
EMISSIONS FACTORS				
Diesel WTW emissions	3.2–3.5 kg CO_2e/L	3.2–3.8 kg CO_2e/L	ICCT (2021), IMO MEPC.391(81)	ICCT Report
Grid carbon intensity (Norway)	18–25 g CO_2e/kWh	18–25 g CO_2e/kWh	NVE, Statnett	NVE, Statnett
Battery manufacturing (LFP)	70 kg CO_2e/kWh (55–90 range)	61–106 kg CO_2e/kWh	IVL (2019)	IVL Publications
OPERATIONAL EMISSIONS				
NO_x emissions range	30–80 t/y	30–80 t/y	NOx Fund, EIAPP	NOx Fund
GHG reduction	92–95%	92–95%	Derived from verified factors	Based on verified data
NOISE IMPACTS				
Noise reduction	10–25 dB (corrected from 40 dB)	10–25 dB (low frequency)	Parsons et al. (2020), Swedish studies	PubMed
Underwater noise	Limited reduction	Propeller noise dominant	Silent@Sea project	IVL Portal
REGULATORY FRAMEWORK				
Zero-Emission Fjords	2026/2032	2026 (small), 2032 (>10,000 GT)	Norwegian Parliament	Regjeringen.no
EU ETS Maritime	From 2024	40% (2024), 70% (2025), 100% (2026)	EU Commission	EU Climate Action
KILE penalties	Revenue-cap system	Active, 12-hour compensation threshold	NVE-RME	Energifakta Norge
OPERATIONAL PARAMETERS				
Annual operating hours	≈7,200 h	7,200–7,300 h plausible	Industry standards	Ferry industry data
Service frequency	Every 30 minutes	Standard for high-frequency routes	Ferry operator data	Public ferry timetables
Docking time	10–15 minutes	Standard for rapid charging	Industry practice	Terminal operations data
Capacity	120 passengers, 35 vehicles	Typical for regional ferries	Vessel specifications	Design standards
METHODOLOGY				
ITU-T L.1480	Tier 2 assessment	Published December 2022	ITU	ITU Standard
Assessment type	Ex-ante	Prospective before deployment	ITU-T L.1480 methodology	Standard method
Effect categories	First, second, higher-order	Comprehensive coverage	ITU-T L.1480	Methodology reference
ENERGY INFRASTRUCTURE				
Grid constraints	Limited capacity at terminals	Common in remote areas	Statnett reports	Statnett
Charging power	High-power required	MW-scale charging	Technical specifications	Derived from docking time
Backup requirements	Emergency generation	Standard practice	Grid code requirements	National grid regulation
BATTERY SPECIFICATIONS				
Chemistry	LFP (Lithium Iron Phosphate)	Safer, longer life	Industry trend	Battery tech reports
Lifecycle	Extended vs NMC	8,000+ cycles typical	NTNU studies	Academic research
Recycling potential	High recovery	Up to 95% recovery	IVL studies	IVL
MARKET CONTEXT				
Norwegian grid mix	90% hydropower	87–90% hydro, 9–11% wind	NVE	NVE
Marginal emissions	45 g winter	Location-based vs marginal	Statnett	Operator data
EU carbon price	Market-based (EUA)	€60–100/tCO_2 (2024)	EU ETS	Ember Data
POLICY ALIGNMENT				
IMO Initial Strategy	50% reduction by 2050	Updated to net-zero 2050	IMO MEPC	IMO Press
Paris Agreement	1.5°C pathway	Alignment confirmed	UNFCCC	UNFCCC
Norwegian climate goals	55% reduction by 2030	From 1990 baseline	Norwegian Government	Regjeringen.no

Table 85: GHG Impact Assessment of Electric Ferry Operations

Section	Claim / Content	Key Findings & Analysis	Primary Sources / Links
Diesel Fuel Emissions Factor	3.2–3.5 kg CO_2e/L (WTW)	ICCT (2021) and IMO MEPC.391(81) (2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels) confirm a range of 3.2-3.8 kg CO_2e/L when adjusted for fuel density and including upstream emissions.	Bryan Comer and Liudmila Osipova, "Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies," ICCT Briefing (March 2021), ICCT Report; IMO MEPC.391(81)
Grid Carbon Intensity (Norway)	18–25 g CO_2e/kWh	Norwegian grid mix (2024): ~90% hydropower, 9% wind, 1% gas and other sources. Low carbon intensity confirmed by renewable energy dominance in Norwegian electricity system.	NVE Annual Energy Statistics, Statnett System Operation, LowCarbonPower, European Environment Agency - Norway (Accessed: November 2025)
Battery Manufacturing (LFP)	70 kg CO_2e/kWh (55–90 range)	Erik Emilsson and Lisbeth Dahllöf (2019) report 61--106 kg CO_2e/kWh for all lithium-ion batteries; LFP batteries typically at the lower end due to simpler chemistry and increasing use of renewable electricity in production facilities.	Erik Emilsson and Lisbeth Dahllöf, "Lithium-Ion Vehicle Battery Production – Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling," IVL Swedish Environmental Research Institute Report C444 (November 2019), IVL Study IVL 2019, PMC 2023
NO_x Emissions	30–80 t/y	Typical Norwegian coastal ferry NO_x emissions fall within documented range. Electrification eliminates direct NO_x emissions; reductions up to 80% achieved through diesel-to-electric conversion.	NOx Fund Annual Reports, Norwegian Maritime Authority - NOx Requirements (Accessed: November 2025)
Noise Reduction	10–25 dB (low frequency)	10-25 dB reduction applies to low-frequency airborne noise from engine elimination; underwater noise reduction varies with propeller design and operational profile.	Marine Noise Studies - PubMed, ScienceDirect Marine Acoustics 2024
Zero-Emission Fjords Policy	2026/2032 deadlines	2026 deadline for ships <10,000 GT; 2032 for ships >10,000 GT in UNESCO World Heritage fjords. Policy confirmed by Norwegian Parliament (Storting) and implemented through Norwegian Maritime Authority regulations.	Norwegian Government Official, UNESCO World Heritage Centre, Nautilus International
EU ETS Maritime Extension	Active from 2024	Phase-in: 40% (2024), 70% (2025), 100% (2026). Applies to vessels >5,000 GT; includes CH_4 and N_2O from 2026.	EU Climate Action, Maersk ETS, ICAP
KILE Penalties	Reliability penalties for outages	Grid operators face revenue caps and 12-hour compensation rules under the CENS/KILE regime.	Energifakta Norge, NVE
Operational Hours	≈ 7,200 h/year	Matches 20 hours/day average operation typical for continuous ferry lines.	Ferry industry operational data
ITU-T L.1480 Methodology	Tier 2 Ex-ante evaluation	Tier 2 captures first-, second-, and higher-order effects; standard for ICT-enabled emission assessments.	ITU L.1480, ITU COP27

Annex I. Template used for collecting the use cases

Proposed template for collecting GIE WG driven use cases

This document includes the used template to collect contributions on AIOTI WG GIE driven use cases.

AIOTI WG Green ICT Enablement (GIE)

Template for Use Case description, to be used in "GHG impact assessment of vertical/cross-domains use cases based on revised ITU-T L.1480 recommendation" report

Version 1, February 2025

This document is a template for the collection of use case descriptions that will be included in the **"GHG impact assessment of vertical/cross-domains use cases based on revised ITU-T L.1480 recommendation"** report.

The annex of this template includes the content that is currently included in Section 3.1.1 of this report on the "Smart Monitoring System in a Windfarm" use case (the content of Section 3.1.1 is not repeated in this annex).

Template Elements:

Use Case Title (provide the name of the use case)

1. **Description** *(see example in Section 3.1.1 of this report)*

- **Motivation:**
- Provide motivation for having this use case from the point of applying ICT to reduce GHG emissions, e.g., is it currently applied and successful.
    - **Please include your motivation input here**:
        - **xxx**
- What are the business drivers, which are the values for the stakeholder types (e.g., several stakeholder types will participate and profit from this use case and at the same time reduce GHG emissions)
    - **Please provide input on business drivers, value for the stakeholder types here**:
        - **xxx**
- **Vertical Sector/domain** where use case is applied: e.g., Energy, Manufacturing, Mobility, Agriculture, Building/City, Health, cross-domain
    - **Please provide input on Vertical Sector/domain or cross domain here**:
        - **xxx**
- **Evaluation Type of the ICT Solution:** What is the Type of evaluation of ICT solution, e.g., pilot, demonstrator, deployed commercial solutions
    - **Please provide input on Evaluation Type of the ICT Solution here**:
        - **xxx**
- **Assessment Time/Type:** What is the Time the GHG emissions assessment needs to take place. (For more details, see key steps and definitions in GHG emission assessment, based on ITU-T L.1480)
    - **Ex-ante**, i.e., a prospective assessment taking place before the assessed operation period of the ICT solution(s);
    - **Mid-way**, i.e., an assessment of a present situation during the operational life of the ICT solution(s);
    - **Ex-post**, i.e., a retrospective assessment that takes place after the assessed operation period of the ICT solution(s).
- **Please provide input on Assessment Time/Type here**:
    - **xxx**

This information is needed in order to define the detailed level of the GHG impact assessment that might be done by the AIOTI WG GIE in the near future;

2. **Source** *(see example in Section 3.1.1)*

- Provide a reference (URL) to the use case, if possible; If not possible, provide details of the relevant (to this use case) activities/projects done by a company/institute/university:
    - **Please provide input on Source here**:
        - **xxx**

3. Roles and Actors – Stakeholders (more details are provided in Section 3.1.1)

Roles: Roles relating to/appearing in the use case

- **Roles and responsibilities** in this use case, e.g., end user, vertical industry, Communication Network supplier/provider/operator, IoT device manufacturer, IoT platform provider, Insurance company, etc.
- **Relationships between the roles**
- **Actors**: Which are the actors with respect to played roles
- Specify if actors are available and willing to be interviewed and provide details/data (in the context of helping the GHG emission assessment)
- **Please provide input on Roles and Actors – Stakeholders here**:
  - **xxx**

4. High-level operations *(see example in Section 3.1.1)*

4.1 High-level operations of the reference scenario of use case that is not applying the ICT solution (Reference scenario)

- Provide a high-level operation of the use case that does not apply the ICT solution to reduce GHG emissions, i.e., which sequence of steps are used in this operation? Provide a high-level illustration
- **Please provide input on High-level operations of the reference scenario here**:
  - **xxx**

4.2 High-level operations of the Green ICT enabled scenario of use case when applying the ICT solution

- Provide a **high-level operation of the use case when the ICT solution is applied** to reduce GHG emissions, i.e., which sequence of steps is used in this operation? Provide a high-level illustration; In particular, describe the main positive effect of applying the ICT solution to reduce GHG emissions in the proposed use case.
- Define and describe the **ICT solution under study,**
- **Please provide input on High-level operations of the Green ICT enabled scenario here**:
  - **xxx**

5. Specify whether you would like to work together with GIE WG colleagues on collecting necessary data to complete the GHG assessment of your use case based on the revised ITU-T L.1480 specification: Yes/Maybe/No *(see example in Section 3.1.1)*

Please provide input whether you would like to work together with GIE WG colleagues on assessment here:

- **xxx**

Contributors

The document was written by several participants of the AIOTI WG GIE.

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About AIOTI

AIOTI is the multi-stakeholder platform for stimulating AI, IoT and Edge Continuum Innovation in Europe, bringing together small and large companies, academia, researchers, policy makers, end-users and representatives of society in an end-to-end approach. We strive to leverage, share and promote best practices in the AI, IoT and Edge Continuum ecosystems, be a one-stop point of information to our members while proactively addressing key issues and roadblocks for economic growth, acceptance and adoption of the AI, IoT and Edge Continuum Innovation in society. AIOTI contributions goes beyond technology and addresses horizontal elements across application domains, such as matchmaking and stimulating cooperation by creating joint research roadmaps, defining policies and driving convergence of standards and interoperability.