

D7.1: Enhanced LCoE model

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Executive Summary

This deliverable presents the enhanced levelized cost of energy (LCoE_e) model developed within Task 7.3 of the INF⁴INiTY project. The model extends the traditional LCoE framework by incorporating socio-environmental externalities, offering a more comprehensive assessment of the true societal cost and value of floating offshore wind energy with nature inclusive design.

The report first defines the full set of cost elements and key performance indicators (KPIs) used in the model, covering techno-economic, environmental, and social dimensions. The techno-economic KPIs include reliability and availability metrics, energy production indicators, and financial metrics. Eighteen environmental KPIs are defined across four categories – climate, water quality, fauna and flora, and other impacts – capturing both costs and potential benefits of floating offshore wind development. Twelve social KPIs address landscape, community, local economy, colocation with other sea users, and broader societal dimensions such as the Social Cost of Carbon and the Social Discount Rate.

The INF⁴INiTY LCoE model is structured around three expenditure components. Capital expenditures (CAPEX) cover development, manufacturing, transport and installation costs; the installation and decommissioning marine operations are estimated using SeaSequence, SINTEF's simulation tool for weather-constrained campaign planning. Operational expenditures (OPEX) are estimated through a probabilistic reliability, availability and maintainability (RAM) model developed by Mondragon University, which captures planned and unplanned maintenance across the wind farm lifetime. Decommissioning expenditures (DECEX) covers the total cost of end-of-life management for components and the decommissioning marine operations. Finally, the annual energy production (AEP) is calculated using DTU-W's minimalistic atmospheric boundary layer model, implemented in PyWake, which accounts for wake losses and farm-scale effects based on site-specific Weibull wind statistics.

The LCoE_e formula augments the traditional LCoE by adding environmental and social components, each of which may be positive (a benefit) or negative (a cost). Environmental impacts are valued using the social cost of carbon for greenhouse gas (GHG) related KPIs and marginal abatement or damage cost approaches for other categories. Social impacts are monetised primarily in €/MW or €/MW-year and cover community benefits, colocation compensation, stakeholder engagement, labour inclusivity, and nature-inclusive design measures. Both components are discounted at the social discount rate rather than the financial discount rate, reflecting society's longer time preferences.

The LCoE_e model is demonstrated through a case study of a 1,005 MW floating offshore wind farm comprising 67 IEA 15 MW reference turbines, located in the Scottish Sea at 100 m water depth and 50 km from shore, consistent with the farm layout defined in INF⁴INiTY D5.2. The baseline financial LCoE is 155.87 €/MWh, with CAPEX dominating at 83% of costs. The environmental LCoE component is -9.69 €/MWh, a net benefit driven primarily by the avoided grid emissions credit. The social LCoE component adds +5.04 €/MWh, dominated by colocation compensation to other sea users and community benefit-sharing schemes. The total LCoE_e is 151.21 €/MWh, marginally below the financial LCoE, reflecting that the environmental benefit of grid decarbonisation more than offsets the added social costs under the baseline assumptions.

A one-at-a-time sensitivity analysis identifies the social discount rate and the financial discount rate as the most influential parameters, followed by the grid emission factor and the social cost of carbon. The results highlight the importance of these macro-economic and policy assumptions in determining the societal attractiveness of investing in floating offshore wind with nature inclusive design.



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List of Abbreviations

Abbreviation	Definition
ABL	Atmospheric boundary layer
AEP	Annual energy production
AHV	Anchor-handling vessel
ARS	Artificial reef structure
ATA	Aquatera Atlantico SL
CAPEX	Capital expenditure
CF	Capacity factor
CLV	Cable laying vessel
CTV	Crew transfer vessel
DECEX	Decommissioning expenditure
DEVEX	Development expenditure
DICE	Dynamic integrated climate economy model
DR	Discount rate - financial
DTU-W	Danmarks Tekniske Universitet - Department of Wind and Energy Systems
EB	Environmental benefits
EC	Environmental costs
EIA	Environmental impact assessment
EoL	End-of-life
EU	Environmental unit
FOW	Floating offshore wind
FOWF	Floating offshore wind farm
FOWT	Floating offshore wind turbine
FSV	Field support vessel
GDP	Gross domestic product
GHG	Greenhouse gas
GICON	GICON-Großmann Ingenieur Consult GMBH
GW	Gigawatt
HLV	Heavy lift vessel
Hs	Significant wave height
Hz	Hertz
IAM	Integrated assessment model
INF ⁴ INITY	Integrated designs for future floating offshore wind farm technology
IRR	Internal rate of return
KPI	Key performance indicator
LCC	Life-cycle cost
LCoE	Levelized cost of energy
LCoE _e	Enhanced levelized cost of energy
LVoE	Levelized value of energy



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MGEP	Mondragon Goi Eskola Politeknikoa Jose Maria Arizmendiarrjeta S COOP
MPA	Marine protected area
MTBF	Mean time between failures
MTTF	Mean time to failure
MTTR	Mean time to repair
MTTW	Mean time to waiting
MW	Megawatt
MWh	Megawatt hour
NID	Nature inclusive design
NIRAS	NIRAS AS
NPV	Net present value
O&M	Operation and maintenance
OAT	One-at-a-time
OECD	Other effective conservation measure
OPEX	Operational expenditure
OSS	Offshore substation
OW	Offshore wind
OWF	Offshore wind farm
Polito	Politecnico di Torino
RAM	Reliability, availability and maintainability
ROI	Return on investment
SCC	Social cost of carbon
SDR	Social discount rate
SINTEF	SINTEF Ocean AS
SME	Small- and medium-sized enterprises
THD	Total harmonic distortion
TLP	Tension leg platform
V	Volt
WACC	Weighted average cost of capital
WINDRAD	Windrad Engineering GMBH
WW	Weather window



1 Introduction

This deliverable presents the enhanced Levelized Cost of Energy model developed within Task 7.3 of the INF⁴INiTY project. The model extends the traditional LCoE framework by incorporating socio-environmental externalities into the economic assessment, thereby offering a more comprehensive and realistic evaluation of the profitability and societal value of investing in floating offshore wind with nature inclusive design.

The LCoE is a widely used metric for assessing the economic competitiveness of energy technologies, expressing the lifetime cost of generating electricity per unit of energy produced. While conventional LCoE frameworks provide a useful baseline for cost comparisons, they typically do not capture the full spectrum of externalities associated with large-scale offshore wind development, including social and environmental impacts. The enhanced LCoE model presented in this deliverable – referred to hereafter as LCoE_e – extends the traditional formulation by incorporating socio-environmental externalities into the economic assessment, thereby offering a more comprehensive and realistic evaluation of the profitability and societal value of investing in floating offshore wind.

The LCoE_e model integrates inputs from several partners within the INF⁴INiTY consortium, as illustrated in Figure 1. Annual energy production (AEP) estimates are provided by DTU-W through the PyWake model. SINTEF provides cost and time estimates for the marine operations related to installation and decommissioning by the SeaSequence model. Mondragon University handles the operational expenditure (OPEX) modelling approach. The environmental modelling related to the LCoE_e is handled by NIRAS while Aquatera has considered the social aspects.

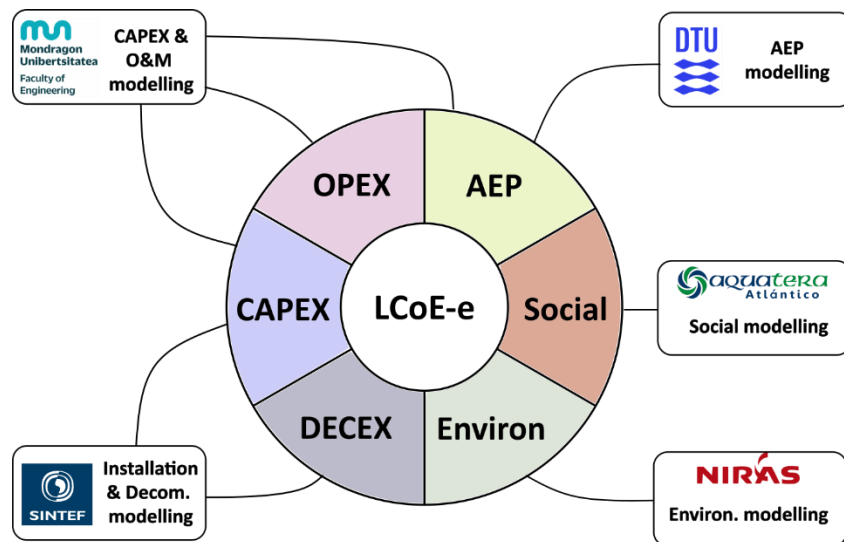


Figure 1: The INF⁴INiTY LCoE_e model

The present report describes the structure and content of the LCoE_e model. Chapter 2 defines all cost elements and key performance indicators (KPIs) considered in the model, spanning techno-economic, environmental, and social dimensions. Chapter 3 details the INF⁴INiTY LCoE model, covering the CAPEX, OPEX, DECEX, and AEP modelling approaches. Chapter 4 presents the enhanced LCoE_e model, incorporating environmental and social externalities. Chapter 5 introduces the case study used to demonstrate and validate the model. Chapter 6 presents results from the case study and sensitivity analysis carried out to identify the most influential parameters and their potential impact on project profitability. Chapter 7 provides conclusions and directions for further work, and finally the Appendix shows an overview of the techno-economic, environmental and social KPIs considered in the model.



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2 Cost elements and KPIs

The purpose of this chapter is to describe all cost elements used in calculating the LCoE and define the KPIs considered most relevant for the INF⁴INiTY project. An overview of cost elements is provided in Section 2.1 and the KPIs are presented in Section 2.2.

2.1 Overview of cost elements

Table 1 provides an overview of the cost elements that are considered in the INF⁴INiTY LCoE model. They have been given a cost category, name and a description.

For components, there are three different categories: manufacturing, transport to marshalling port, and end-of-life management. The first two ones are associated with the CAPEX, while the latter is associated with the DECEX. Installation, dismantling and operation and maintenance (O&M) costs related to components are handled by the INF⁴INiTY models for installation, decommissioning and O&M based on vessel, port and repair costs.

Table 1: Definitions of cost elements in INF⁴INiTY's LCoE model

Cost category	Name	Description
Development	Development costs	All costs associated with project development and consenting, including activities as site identification, feasibility studies, environmental impact assessments, permitting and regulatory compliance.
Component manufacturing	Turbine generator	All costs associated with the manufacturing of a turbine generator. Cost provided as € per item.
	Turbine blade	All costs associated with the manufacturing of a turbine blade. Cost provided as € per item.
	Tower	All costs associated with the manufacturing of the tower of the floater. Cost provided as € per item.
	Substructure	All costs associated with the manufacturing of the substructure of the floater. Cost provided as € per item.
	Anchor	All costs associated with the manufacturing of an anchor. Cost provided as € per item.
	Chain	All costs associated with the manufacturing of a chain. Cost provided as € per item.
	Inter-array cable	All costs associated with the manufacturing of inter array cables. Cost provided as €/m.
	Export cable	All costs associated with the manufacturing of export cables. Cost provided as €/m.



	Substation	All costs associated with the manufacturing of a substation. Cost provided as € per item.
	Substation substructure	All costs associated with the manufacturing of the substructure of a substation. Cost provided as € per item.
	Substation anchor	All costs associated with the manufacturing of an anchor for a substation. Cost provided as € per item.
	Substation chain	All costs associated with the manufacturing of a chain for a substation. Cost provided as € per item.
Component transport to marshalling port	Turbine generator	All costs associated with the transportation of a turbine generator from manufacturing site to marshalling port. Cost provided as € per item.
	Turbine blade	All costs associated with the transportation of a turbine blade from manufacturing site to marshalling port. Cost provided as € per item.
	Tower	All costs associated with the transportation of the tower of the floater from manufacturing site to marshalling port. Cost provided as € per item.
	Substructure	All costs associated with the transportation of the floater substructure from manufacturing site to marshalling port. Cost provided as € per item.
	Anchor	All costs associated with the transportation of an anchor from manufacturing site to marshalling port. Cost provided as € per item.
	Chain	All costs associated with the transportation of a chain from manufacturing site to marshalling port. Cost provided as € per item.
	Inter-array cable	All costs associated with the transportation of inter array cables from manufacturing site to marshalling port. Cost provided as € per item.
	Export cable	All costs associated with the transportation of export cables from manufacturing site to marshalling port. Cost provided as € per item.
	Substation	All costs associated with the transportation of a substation from manufacturing site to marshalling port. Cost provided as € per item.



	Substation substructure	All costs associated with the transportation of a substation substructure from manufacturing site to marshalling port. Cost provided as € per item.
	Substation anchor	All costs associated with the transportation of an anchor to a substation from manufacturing site to marshalling port. Cost provided as € per item.
	Substation chain	All costs associated with the transportation of a chain to a substation from manufacturing site to marshalling port. Cost provided as € per item.
Component end-of-life management	Turbine generator	All costs associated with the end-of-life management of a turbine generator after transportation to port. Cost provided as € per item.
	Turbine blade	All costs associated with the end-of-life management of a turbine blade after transportation to port. Cost provided as € per item.
	Tower	All costs associated with the end-of-life management of the tower of the floater after transportation to port. Cost provided as € per item.
	Substructure	All costs associated with the end-of-life management of the substructure of the floater after transportation to port. Cost provided as € per item.
	Anchor	Anchors are assumed to be left in place when decommissioning the wind farm. Hence no costs are expected.
	Chain	All costs associated with the end-of-life management of a chain after transportation to port. Cost provided as € per item.
	Inter-array cable	All costs associated with the end-of-life management of an inter array cable after transportation to port. Cost provided as € per item.
	Export cable	All costs associated with the end-of-life management of an export cable after transportation to port. Cost provided as € per item.
	Substation	All costs associated with the end-of-life management of a substation after transportation to port. Cost provided as € per item.



	Substation substructure	All costs associated with the end-of-life management of a substructure to the substation after transportation to port. Cost provided as € per item.
	Substation anchor	Substation anchors are assumed to be left in place when decommissioning the wind farm. Hence no costs are expected.
	Substation chain	All costs associated with the end-of-life management of a chain for the substation after transportation to port. Cost provided as € per item.
Vessel	Day rate	The daily cost of chartering a given vessel. Includes costs of crew but not fuel costs. Cost provided as € per day for a given vessel.
	Mobilisation cost	The cost of mobilising a vessel, i.e. preparing the vessel for the work to be done. Cost provided as € for a given vessel.
	Demobilisation cost	The cost of demobilising a vessel, i.e. any costs involved when the vessel has finalised the work it was prepared to do. Cost provided as € for a given vessel.
	Fuel cost	The cost of the fuel used by the vessel. Cost provided as €/unit of fuel (e.g. litre, m ³ etc.).
Port	Investment cost/fixed cost	Any costs involved in preparing a port for the operations required while serving the offshore wind farm. Cost provided as € for a given port.
	Daily cost	Any daily costs involved in using a port during operation. Cost provided as € per day for a given port.
Repairs	Manual reset cost	All costs associated with manual reset of a turbine following a fault that cannot be resolved remotely.
	Minor repair cost	All costs associated with minor corrective maintenance activities requiring limited spare parts and no major component replacement.
	Medium repair cost	All costs associated with corrective maintenance requiring partial component replacement and moderate offshore intervention
	Major repair cost	All costs associated with extensive corrective maintenance involving significant component repair or overhaul but not full component replacement.



	Major replacement cost	All costs associated with complete replacement of a major component requiring heavy-lift vessel operations and significant offshore logistics.
	Annual service cost	All costs associated with an annual service of a turbine.
	Floater minor failure	All costs associated with a minor failure of the floater.
	Array cable replacement	All costs associated with a needed replacement of an array cable.
	Technician cost	All labour-related costs associated with technicians performing inspection, maintenance, reset, repair, and replacement activities.

2.2 Overview of KPIs

The KPIs found most relevant for the INF⁴INiTY project are defined in this chapter. They have been divided into Techno-economic (Section 2.2.1), environmental (Section 2.2.2) and social (Section 2.2.3).

2.2.1 Techno-economic

The techno-economic KPIs can be classified into technical and economic indicators. This section provides a description of the most relevant KPIs, while a summary of all KPIs is presented in Table 20 in the Appendix.

2.2.1.1 Technical KPIs

The technical KPIs can be divided into Reliability, Availability, and Maintainability (RAM) KPIs, and those related to power and energy, which together capture system performance, operational robustness and energy output.

Within RAM KPIs, system performance is assessed in terms of reliability, availability and maintainability, capturing the ability to operate without failure, remaining accessible when needed, and efficiently restored after downtime. The main metrics considered within the RAM category are:

- **KPI T1** - Mean Time to Failure (MTTF) measures the average expected operating time until the first failure of an item occurs, expressed in hours.
- **KPI T2** - Mean Time Between Failures (MTBF) quantifies the average time between consecutive failures during operation, expressed in hours.
- **KPI T3** - Mean Time to Repair (MTTR) represents the average time required to restore the system to full operational condition after a failure, indicating maintainability efficiency, expressed in hours.
- **KPI T4** - MTTW (Mean Time to Waiting) accounts for delays before maintenance or repair actions can begin, such as those caused by resource constraints, logistics or metocean conditions, expressed in hours.
- **KPI T5** - Accessibility evaluates the ease with which the system or its components can be physically reached and serviced, influencing maintenance speed and downtime, expressed as a percentage.
- **KPI T6** - Time-based availability expresses the proportion of time the system is operational relative to the total time considered, offering a temporal measure of uptime, expressed as a percentage.

Within power- and energy-related KPIs, system performance is evaluated in terms of power output, energy production and efficiency, capturing the ability to deliver the required power reliably, maintain high energy yield and operate within quality standards. The main metrics considered within power- and energy-related KPIs are:

- **KPI T7** - Power density measures the amount of power generated per unit area of the system, reflecting the efficiency of space utilization, expressed in watts per square meter.
- **KPI T8** - Power quality evaluates the stability and consistency of the electrical output, including parameters such as voltage, frequency, and harmonic distortion, which affect the reliability of energy supply, typically expressed in volts (V), hertz (Hz), and percentage of total harmonic distortion (%THD).
- **KPI T9** - Annual Energy Production (AEP) represents the total electrical energy generated by the wind farm over a year, providing a measure of its energy yield, expressed in megawatt-hours per year (MWh/year).
- **KPI T10** - Capacity Factor (CF) is the ratio of the actual energy produced over a period to the maximum possible energy the system could have generated if it operated at full rated power continuously, expressed as a percentage (%).
- **KPI T11** - Curtailment ratio quantifies the proportion of potential energy generation that is intentionally reduced or not delivered due to system constraints, grid requirements, or safety considerations, expressed as a percentage (%).

2.2.1.2 Economic KPIs

Within economic KPIs, system performance is evaluated in terms of investment and lifecycle costs, as well as financial returns, capturing both the economic feasibility and profitability of the project. The key indicators considered are:

- **KPI T12** - Capital Expenditure (CAPEX) represents the total upfront cost required to design, manufacture and install the wind farm, expressed in €.
- **KPI T13** - Operational Expenditure (OPEX) measures the recurring costs for operating and maintaining the system over its lifetime, expressed in €.
- **KPI T14** - Decommissioning Expenditure (DECEX) quantifies the costs associated with dismantling and safely disposing of the system at the end of its operational life, expressed in €.
- **KPI T15** - Life-Cycle Cost (LCC) captures the total cost of ownership over the wind farm's entire life, including CAPEX, OPEX and DECEX, expressed in €.
- **KPI T16** - Levelized Cost of Energy (LCoE) represents the average cost per unit of energy generated over the wind farm's lifetime, accounting for all costs and energy produced, expressed in monetary units per megawatt-hour (€/MWh).
- **KPI T17** - Levelized Value of Energy (LVoE) quantifies the average revenue or value obtained per unit of energy produced over the system's lifetime, expressed in monetary units per megawatt-hour (€/MWh).
- **KPI T18** - Internal Rate of Return (IRR) indicates the expected annualized rate of return on the investment, expressed as a percentage (%).
- **KPI T19** - Net Present Value (NPV) represents the difference between the present value of cash inflows and outflows over the project lifetime, expressed in €.
- **KPI T20** - Return on Investment (ROI) measures the ratio of net profit to the total investment, providing a simple indicator of project profitability, expressed as a percentage (%).

2.2.2 Environmental

The environmental KPIs have been divided into the following overall environmental impact categories:

- Climate impacts
- Water quality impacts
- Fauna and flora impacts



- Other

In the following sections each of the categories are presented and the suggested KPIs for each of them are listed. The listed KPIs represent a gross list of possible – or likely – environmental impacts but it is not all impacts and KPIs that are relevant to all projects and geographical areas. The list is based on expert input from biologists, marine biologists and other experts experienced with the assessment of environmental impacts from offshore wind turbines. Their input has been supplemented by a review of relevant available environmental impacts assessments of offshore wind turbine parks. Because it is a gross list of potential environmental impacts and KPIs, the list should be used with due regard to the characteristics of the specific project under consideration.

A summary table of the KPIs listed in this section can be found in the Appendix, Table 21.

2.2.2.1 Climate

The climate impacts during operation (KPI E1-3) and the whole life-cycle (KPI E4) of the offshore wind farm can be divided into the following:

- **KPI E1** – Avoided greenhouse (GHG) gas emissions: The renewable energy from the wind turbines displaces fossil fuels and the related GHG-emissions.
- **KPI E2** – Additional carbon uptake: Due to better living conditions for flora and fauna on the underwater constructions (both benthic and pelagic zone) carbon uptake and sequestration is increased.
- **KPI E3** – Release of sequestered carbon: Disturbance of the sea floor can lead to the release of sequestered carbon and/or less favourable living conditions for the benthic flora and fauna and thus reduced carbon uptake and sequestration.
- **KPI E4** – GHG-emissions from fossil-based activities in all phases of the project: During production of the wind turbines and other constructions fossil fuels are likely to be an input in the processes. This leads to GHG-emissions. The same applies to the phases of operation and decommissioning of the wind farm.

The avoided greenhouse gas emissions (KPI E1) and Additional carbon uptake (KPI E2) are positive impacts – or benefits – of the project, whereas the release of sequestered carbon (KPI E3) and GHG-emissions from fossil-based activities (KPI E4) are adverse impacts or costs to the wider society.

2.2.2.2 Water quality

Construction and operation of an offshore wind farm can affect the water quality in a number of ways, which is reflected in the following KPIs:

- **KPI E5** – Increased nutrient load: Phosphorus and nitrous can be released to the marine environment during construction or if aquacultural activities are part of the project.
- **KPI E6** – Removal of nutrients: Phosphorus and nitrous can be removed (resulting in improved oxygen levels) if the flora and fauna are stimulated e.g. through the harvesting of mussels or clams from the underwater constructions and nature-inclusive designs (NIDs).
- **KPI E7** – Release of chemicals and other pollutants: During all phases of the project chemicals and other pollutants can be released to the environment in small quantities or unintendedly in larger amounts.
- **KPI E8** – Uptake and possible removal of chemicals and other pollutants: If parts of the flora and fauna are harvestable chemicals and other pollutants can be removed from the environment.

Again, there are possibly positive environmental impacts if nutrients or chemicals are removed and negative environmental impacts if more nutrients or chemicals are released to the environment.

2.2.2.3 Fauna and flora

A distinction can be made between sessile (or immobile) and mobile fauna and flora and that distinction applies to both the marine and the terrestrial environments.

During operation, the offshore wind farm and its underwater constructions can protect the benthic habitats from disturbance from fisheries, harvesting of sand, gravel and rocks from the seabed, dumping of dredged material and other human activities affecting the benthic habitats. The associated related KPIs are:

- **KPI E9** – Protection of benthic vegetation: Corals, sponges, algae, seagrass etc.
- **KPI E10** – Protection of benthic fauna: Filter feeders, fry and spat.
- **KPI E11** – Increased (or decreased) diversity in flora and fauna (sessile and mobile): With the protection of benthic habitats comes – in some instances – increased biodiversity.
- **KPI E12** – More (or less) rare and protected species (sessile and mobile): Protected species (including marine mammals and birds) populations may fluctuate.
- **KPI E13** – Changes in commercial species (sessile and mobile): Commercial species (typically mostly fish stocks) can be increased or decreased.
- **KPI E14** – More (or less) invasive species (sessile and mobile): If the environmental conditions are favourable (or becomes less favourable) invasive species (including marine mammals and birds) can become dominating (or reduced in numbers).

2.2.2.4 Other environmental KPIs

In addition to the environmental KPIs presented in the previous subsections 2.2.2.1-2.2.2.3, other potential environmental impacts of the construction and operation of the offshore wind farm:

- **KPI E15** – (Adverse) Visual impacts of the offshore installations which predominantly affect human wellbeing i.e. people.
- **KPI E16** – Noise pollution during construction, operation and decommissioning of the offshore wind farm. This can affect not only human wellbeing but also fauna e.g. sea mammals (whales, seals, dolphins etc.) susceptible to the noise from construction, the blades of the wind turbines or vessels servicing the turbines.
- **KPI E17** – Changes in air quality particularly during construction, operation and decommissioning of the wind turbines can be linked to operating vessels. Increased levels of particulate matter and nitrous oxides can lead to worsened air quality.
- **KPI E18** – Reduction of the human use value of the deployment areas (restrictions of access) is the flip side of the potential protection of vegetation and fauna addressed under KPIs E9 and E10. Typical use values that can be affected by an offshore wind farm are fisheries (commercial and recreational) and leisure use of the area (boating, diving, tour boats etc.).

2.2.3 Social

The following indicators have been revised to support a comprehensive assessment of socioeconomic dimensions within Floating Offshore Wind (FOW) development inclusive of ARS as a NIDs approach. These were selected based on the potential social impacts concerning the population, stakeholder interests, and local communities across the different phases of project development, and best practices identified through literature review and tenders.

The KPIs selection considers the most up-to-date tendering processes across Europe (including AO5, AO6 and AO8 in France; bids N3.5, N7.2, N9.1–N9.3, N10.1 and N10.2 in Germany; IA in the Netherlands; as well as INTOG in Scotland and NYSEDA in the United States), together with emerging insights from recent research and consultation processes.

It is assumed that the offshore wind project complies with all required environmental and social impact assessment procedures, and that the main environmental and social impacts have been identified, mitigated, and managed in

accordance with applicable regulatory and planning requirements. Therefore, the proposed KPIs focus on the residual socioeconomic effects, community-related aspects, and broader social value generated throughout the project lifecycle.

Together, these indicators capture key social, economic, and territorial aspects influencing project acceptance, operational feasibility, and overall value generation. The analysis provides a more balanced and robust representation of socioeconomic KPIs and their potential contribution to the enhanced Levelized Cost of Energy (LCoE-e) and wider project outcomes.

The social indicators (KPI S) have been divided into the following overall categories:

- Social acceptance and licence to operate
- Regional economic development
- Social macroeconomics

A summary table of all listed KPIs can be found in Appendix Table 22.

Within each category, there are indicators expected to influence the enhanced Levelized Cost of Energy (LCoE_e); whereas others are not quantified within the LCoE_e equation but considered relevant to avoid a biased approach to the social dimension. Therefore, both KPIs and the mechanism of expression in the LCoE_e are defined within each category.

2.2.3.1 Social acceptance and license to operate

Social acceptance and license to operate is one of the major subjects to any renewable energy project. KPIs to be considered when obtaining social licenses to operate are at least the following.

KPIs S1 – S4 are related to those derived from attachment, perception, emotional response and cultural assets.

- **KPI S1** – Place attachment: Measures the emotional, cognitive and behavioural bonds that individuals and communities develop with places over time. It reflects sense of belonging, identity, and personal or collective meaning associated with a location. This indicator is inherently subjective and plays a key role in shaping social acceptance, cohesion, and potential responses to development.
- **KPI S2** – Cultural landscapes: Assesses the historical, social and cultural significance of landscapes, through tangible and intangible heritage elements that may be affected by the project. Heritage captures the inherent cultural value, inclusive of cultural assets, traditional uses, and collective memory, supporting the identification of sensitivities, potential impacts, and opportunities for mitigation or co-benefits.
- **KPI S3** – Environmental impact perception: Captures deeper insights into the reasons behind impact perceptions upon nature, which may be driven by emotional responses, contextual factors, representation of system of beliefs, or social bias when project pressures information is not promptly available.
- **KPI S4** – Technology acceptance (NIDs): Technology acceptance may be driven by emotional responses, contextual factors, previous experiences, representation of system of beliefs, and social bias. Inclusion of Nature Inclusive Design—such as artificial reef structures (ARS)— may influence public perception. Approaches and social response are site and context specific.

KPIs S5 – S7 are key community dimensions that strongly contribute to social equity and therefore, acceptance and license.

- **KPI S5** – Community benefits scheme: Measures the financial contributions provided by offshore wind developers to host communities, typically expressed as annual payments per installed MW. These schemes deliver direct economic value outside formal planning obligations, supporting local initiatives, infrastructure, and community well-being. While relatively small compared with total project revenues, they play a significant role in enhancing perceived fairness and strengthening the link between project development and local socio-economic benefits.
- **KPI S6** – Community ownership: Evaluates the extent to which local stakeholders participate financially in offshore wind projects through credible ownership structures (e.g. joint ventures, shared revenue, or split ownership of assets). This KPI captures the degree to which community meaningfully participate in investment, governance, and revenue management reflecting mechanisms that promote local empowerment, strengthen trust, and support

long-term social license. It represents a tangible mechanism to align project value creation with local economic participation.

- **KPI S7** – Community trust and engagement: Assesses the quality, inclusiveness, and effectiveness of stakeholder engagement processes throughout the project lifecycle. It captures the extent to which transparent communication, early consultation, and continuous dialogue bridges FOW development to local knowledge, values, concerns and needs, to inform decision-making. Early and consistent engagement builds trust, reduces conflict, enhances legitimacy, and supports a fair and socially responsible energy transition.

2.2.3.2 Regional economic development

Regional and local economic development is a well-recognized direct benefit arising from the construction of floating offshore wind (FOW) infrastructure. Key indicators foster socioeconomic growth and leverage of capacity.

- **KPI S8** – Labour inclusivity (vulnerable groups): Measures the extent to which offshore wind projects promote equitable access to employment and training opportunities for underrepresented or vulnerable groups (e.g. long-term unemployed, people with disabilities, low-qualified individuals). It is quantified through targeted work and training hours across project phases and reflects the project's contribution to social equity, local capacity building, and inclusive economic development.
- **KPI S9** – Training and employment of apprentices: Evaluates the level of investment in apprenticeships and structured training pathways that support workforce development and industrial capability. By allocating dedicated employment and training hours to apprentices and early-career professionals, this KPI reflects efforts to build technical skills, enhance job quality, and strengthen long-term sector resilience. It supports innovation, regional competitiveness, and the sustainability of the offshore wind workforce.
- **KPI S10** – Co-location and Sea-Use Interactions: Assesses the socio-economic impacts, risks, and opportunities associated with the interaction between offshore wind projects and existing sea uses, including navigation and other industries. These interactions may generate direct and indirect costs or opportunities due to co-location added value. This KPI is related to environmental KPI E18 – but consider the social aspects.
- **KPI S11** – Employment: Measures the capacity of offshore wind development to generate direct and indirect employment and associated economic value. Estimates suggest that large-scale deployment could support approximately one direct and one indirect job per-MW installed spanning the full project lifecycle, alongside high value-added per employee. Construction and O&M represent the most significant sources of labour demand. This KPI captures both the scale and quality of employment, highlighting its contribution to regional economic development and social value creation.
- **KPI S12** – Local Small and Medium Enterprise (SMEs) engagement: Evaluates the extent to which small and medium-sized enterprises (SMEs) participate in offshore wind projects across design, manufacturing, construction, and operations and maintenance phases. SME involvement supports local industrial capacity, enhances supply chain resilience, and promotes more equitable distribution of economic benefits.

By facilitating access to large-scale infrastructure projects, SME engagement contributes to business growth, skills development, and regional competitiveness. This KPI reflects the role of offshore wind in strengthening local economies, fostering innovation, and ensuring that economic opportunities are accessible beyond large contractors.

2.2.3.3 Social macroeconomics

Social macroeconomics examines how large-scale economic policies and developments affect social well-being. It focuses on the interaction between economic systems and societal factors.

The most relevant social macroeconomics for social welfare is the **social cost of carbon (SCC)** and the **social discount rate (SDR)**. Neither of these are KPIs themselves but act as economic factors upon other indicators.



KPIs E1 to KPI E4 analyse carbon displacement across these environmental indicators and are directly relevant for applying the social cost of carbon (SCC)¹, whilst SDR is eligible when the project in question treats valuation of present versus future welfare and risk at a societal level and is aligned with public policy objectives rather than private financial returns (e.g. climate infrastructure).

The economic treatment of these factors is described below:

The **social cost of carbon (SCC)** factor seeks to estimate the economic damage from emitting one tonne of carbon dioxide at a geographical point and in a determinate moment². Carbon emissions contribute to climate changes, which derive into increased temperatures, rising sea levels, and increased frequency of extreme weather events, among others. These physical damages affect economic outcomes, such as GDP, productivity or welfare. The damage of carbon increases when the concentration of greenhouse gases is higher, therefore, as climate impacts are on the rise, the SCC is expected to increase over time.

SCC is often obtained by using Integrated Assessment Models (IAMs) which link the climate system to socio-economic schemes to estimate the impact of carbon emissions on social welfare. These models are based on historic data, assumptions and scenarios³.

The **social discount rate (SDR)** determines the weight society gives to consumption at different time periods. The general idea is that consumption today is preferred over consumption in the future. There is an intrinsic co-relation between SDR and SCC. For the estimation of SCC, the SDR weights future benefits and damages. Generally, a higher SDR results in lower SCC as future damages are weighted less. However, for the purpose of macro-economic analysis, these factors are treated independently.

¹ And also for the life-cycle assessment to be performed in the INF4INITY project.

² Carbon values literature review. Prepared for BEIS by Vivid Economics, BEIS research paper number: 2021/049. <https://assets.publishing.service.gov.uk/media/613f61ae8fa8f503c4b208e8/carbon-values-lit-review.pdf>

³ Some of the most well-known IAM for SCC analysis globally is the DICE (Dynamic Integrated Climate Economy) model, but alternatives exist including PAGE (as used in the Stern Review) and FUND.



3 The INF⁴INiTY LCoE model

Estimating the costs and energy production of floating offshore wind farms (FOWFs) is crucial for understanding their economic feasibility. This task is challenging due to the limited number of commercial operating FOWFs, as most existing projects are still in the research or development phase. However, the development of a model to determine the average annual energy production (AEP) and breaking down the components of FOWFs helps assess the total costs. INF⁴INiTY aims to elucidate the AEP and the various costs associated with the installation, operation and maintenance (O&M), and decommissioning of FOWFs. Recent investigations of the economic feasibility of FOWFs have been carried out for different predefined regions, such as Portugal⁴, the European part of the Atlantic Ocean⁵, and the North of Spain⁶. However, these investigations generally lack details of the basic parameters characterizing the wind farm layout and their wake losses, and there is a need for a model that takes into account the main features of FOWFs to provide a fast and accurate predictive tool for assessing site-dependent energy production and costs.

This chapter presents the general levelized cost of energy (LCoE) model used in the INF⁴INiTY project. The LCoE model consists of the total technical cost of the offshore wind farm over its lifetime divided by the total energy production, all adjusted by the discount rate, as described in the following equation:

$$LCoE = \frac{CAPEX + \sum_{t=1}^T \frac{OPEX_t}{(1+r)^t} + \frac{DECEX}{(1+r)^T}}{\sum_{t=1}^T \frac{AEP_t}{(1+r)^t}} \quad (1)$$

Here, CAPEX is the capital expenditures, consisting of all investment costs, including project development, manufacturing and installation costs for the offshore wind farm. OPEX is the operational expenditures, all costs involved in the operation and maintenance phase of the offshore wind farm. DECEX is decommissioning expenditures, and AEP the annual energy production. The discount rate is r , and T is the total expected lifetime (in years) of the offshore wind farm.

In the following, the CAPEX and DECEX modelling approach used in INF⁴INiTY is described in Section 3.1, the OPEX modelling approach in Section 3.2, and finally the AEP modelling approach in Section 3.3.

3.1 CAPEX and DECEX modelling approach

The CAPEX modelling approach in INF⁴INiTY breaks total capital expenditure into four main components: development costs (C_{dev}), manufacturing costs (C_{mf}), transportation cost to marshalling port C_{trans} and installation costs (C_{inst}):

$$CAPEX = C_{dev} + C_{mf} + C_{trans} + C_{inst} \quad (2)$$

Project development and consenting costs include activities such as site identification, feasibility studies, environmental impact assessments, permitting and regulatory compliance.

Manufacturing costs comprise the production of floating wind turbine systems and the associated electrical infrastructure (transmission costs). The FOWT cost includes turbines, floating platforms, mooring systems and anchors, each estimated using scaling relationships based on capacity, material quantities, and water depth. Transmission costs

⁴ Castro-Santos, L., Silva, D., Bento, A.R., Salvação, N. and Soares, C.G. Economic feasibility of floating offshore wind farms in Portugal. *Ocean Engineering*, 207, 107393, 2020. DOI: 10.1016/j.oceaneng.2020.107393

⁵ Martinez, A. and Iglesias, G. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. *Renewable and Sustainable Energy Reviews*, 154, 111889, 2022. DOI: 10.1016/j.rser.2021.111889

⁶ Castro-Santos, L., Filgueira-Vizoso, A., Lamas-Galdo, I. and Carral-Couce, L. Methodology to calculate the installation costs of offshore wind farms located in deep waters. *Journal of Cleaner Production*, 170, 1124–1135, 2018. DOI: 10.1016/j.jclepro.2017.09.219



include export cables, inter-array cables, and the offshore substation, typically scaled with distance to shore and installed capacity.

Transportation cost to marshall port includes all costs of transporting components of the floating wind turbine systems and the electrical infrastructure from manufacturing site to marshall port. Transportation can be both land-based and sea-based.

Installation costs include all activities required for offshore transportation, assembling, and deploying the wind farm components at the project site. This encompasses turbine and platform installation, mooring and anchoring operations, cable laying (both inter-array and export), and offshore substation installation. These costs are typically driven by factors such as water depth, distance to shore, vessel requirements and installation time, and are estimated using simulation-based approaches to capture operational complexity and logistics. The simulation-based approach used to estimate installation costs in INF⁴INITY is described in Section 3.1.1.

The DECEX modelling approach in INF⁴INITY breaks total decommissioning expenditure into two main components: decommissioning costs (C_{dec}) and end-of-life costs (C_{eof}):

$$DECEX = C_{dec} + C_{eof} \quad (3)$$

Decommissioning costs include all activities related to dismantling the wind farm components at the project site and the offshore transportation of the components to port. In INF⁴INITY a simulation-based approach is used to estimate these costs, similar to the approach for installation cost estimation, described in Section 3.1.1.

End-of-life costs are all costs associated with end-of-life management of the wind farm components after being dismantled and transported to port.

3.1.1 Installation and decommissioning costs

Installation and decommissioning costs, i.e., all costs associated with the marine operations, for installation and decommissioning, are estimated using SeaSequence, a simulation tool provided by SINTEF Ocean. SeaSequence evaluates sequences of marine operations by estimating expected performance and associated risks under realistic weather conditions, and is used, for example, for planning an installation or maintenance campaign and for development of new equipment and procedures. SeaSequence follows a discrete-event simulation approach where a simulation model is constructed by defining a system of operations and policies: operations specify weather requirements, expected durations, necessary vessels, and how they influence the system state, while policies determine the selection of the next operation based on the current system state. At a high level, the campaign is treated as a sequence of weather-constrained operations executed by a given set of assets, and the policy module supports both multiple vessels operating in parallel and joint operations that require several assets.

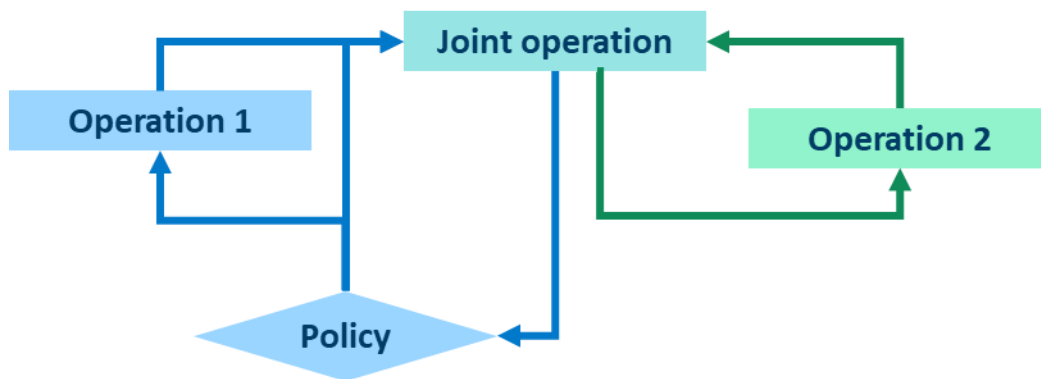


Figure 2: Example model structure



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This report is currently under review by CINEA. Its contents are provisional and may be subject to change following the review process.

Figure 2 illustrates an example of such a model structure, where two operations can be executed independently and a joint operation represents a coordinated task requiring multiple assets, with the policy module governing which operation is selected next based on the system state. For a given case, each operation is specified with metocean criteria defined either as a maximum significant wave height or as an H_s - T_p function, wind limits, a required weather window length, an operation duration, required vessels and resources, and the operation's effect on the system state. When multiple next operations are feasible for a vessel (or another type of asset), the policy module selects the next operation using the current system state.

The simulations are performed using historical weather data covering multiple years (e.g., 30 years) for the relevant location. For each calendar day of the year, the campaign is simulated with that day as the operation start date, and this is repeated across all available weather years, yielding one outcome per weather year (e.g., 30 outcomes) for each start date. During each run, every vessel's (or any other asset's) state is logged at each time step, and key metrics are computed, such as campaign duration, waiting-on-weather, and expected costs (and emissions, if included). Aggregating across weather years provides an estimate of the expected value and variability of these metrics for each start date. Figure 3 shows an example output where the expected campaign duration is reported as a function of operation start date for a given case, illustrating the seasonal variation in campaign duration driven by metocean conditions and waiting-on-weather.

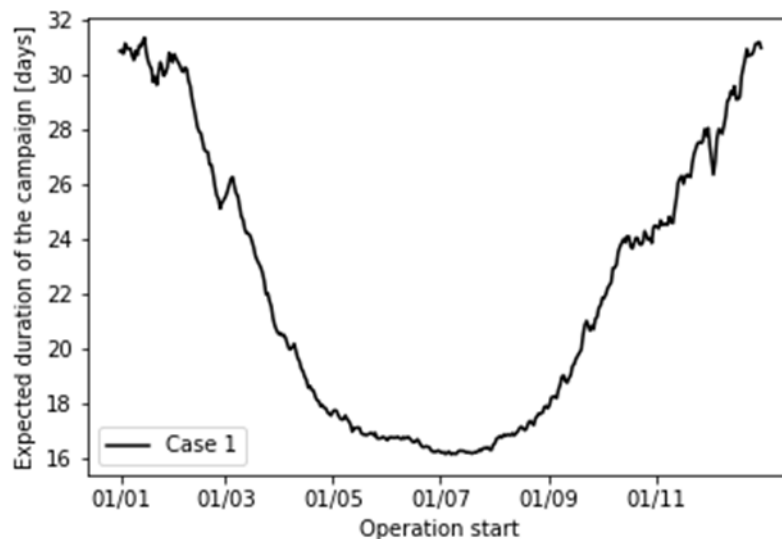


Figure 3: Example output from SeaSequence.

The outputs used here are the simulated vessel charter times, which are mapped to the vessel cost elements in the LCoE model: day rate, mobilisation cost, demobilisation cost, and fuel cost and consumption. For each vessel v , the chartering cost contribution is computed as $C_v = M_v + D_v + r_v T_v + F_v$, where T_v is the simulated charter time (days), r_v is the day rate, M_v and D_v are mobilisation and demobilisation costs, and F_v represents fuel costs if included via a fuel consumption model. The total vessel chartering cost for the campaign is $C = \sum_{v \in V} C_v$.

Floating offshore wind campaign models

In the installation campaign case used for evaluation, the SeaSequence model is structured as one overall system composed of four connected subsystems that represent the main phases of the floating wind farm installation. The



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subsystems are (i) anchor installation, (ii) mooring line installation, (iii) towing and hook-up of floater and turbine, and (iv) cable installation. The decomposition into the four subsystems is shown in Figure 4:

Each subsystem is represented as an internal sequence of operations governed by its own policy decisions. This can include mobilisation and transit, execution of the relevant offshore tasks under metocean constraints, and transit back to port. In the current case representation, the anchor installation subsystem includes operations such as loading anchors, transiting to the wind farm, installing anchors, and returning to port. The mooring line subsystem includes loading mooring lines, transiting, installing mooring lines, and returning to port. The towing and hook-up subsystem includes preparing towing, towing to the wind farm, hook-up of the floater, and returning to port. The cable installation subsystem includes loading cables, transiting, installing cable sections, and returning to port.

The subsystems are linked through dependency rules that determine when downstream work is allowed to proceed. In the installation case, these dependencies enforce a sequential campaign. Mooring line installation is only allowed to proceed after all anchors have been installed, towing and hook-up is only allowed to proceed after all mooring lines have been installed, and cable installation is only allowed to proceed after all floaters have been hooked up. In SeaSequence it is also possible to allow for some of this work to be executed in parallel.

A key modelling choice in this installation case is that each subsystem can be refined independently without increasing the complexity of the other subsystems. More detail can be added within a subsystem, for example by splitting offshore tasks into multiple steps or modelling multiple parallel vessels within the same subsystem. The interaction between subsystems remains captured through a small set of progress counters and dependency rules that determine when each phase is allowed to progress.

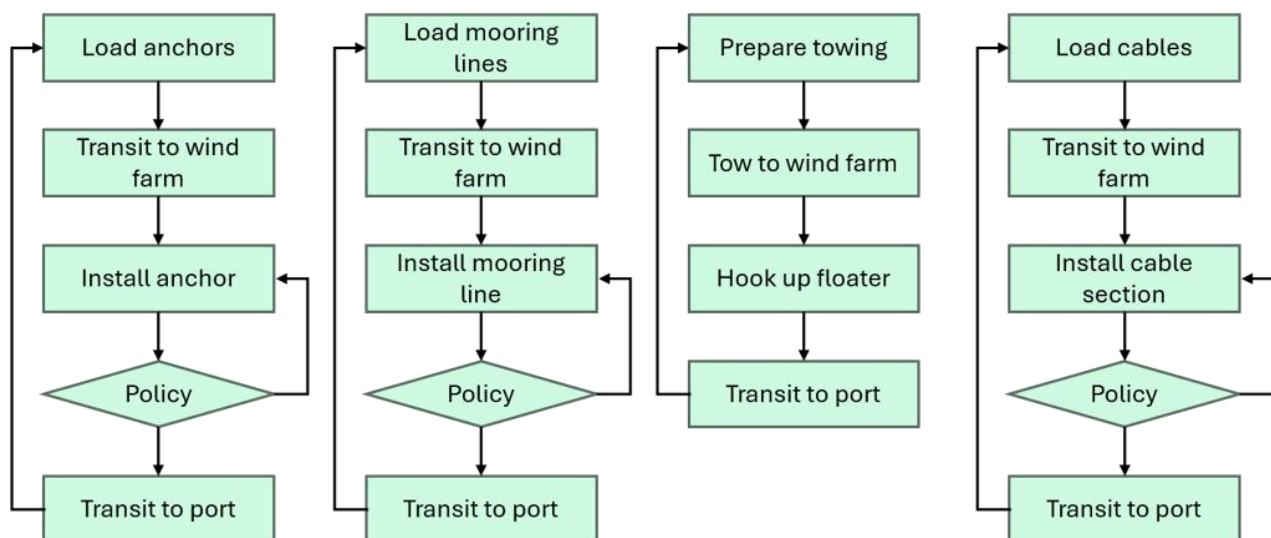


Figure 4: Installation campaign case, structured as one overall system with four subsystems covering anchor installation, mooring line installation, towing and hook-up of floater and turbine, and cable installation.

In the decommissioning campaign case used for evaluation, the SeaSequence model follows the same overall modelling principles as the installation case, but with a dedicated set of subsystems and dependency rules tailored to end-of-life activities. The decommissioning model is defined to follow the reverse main order compared with installation and is represented using three subsystems covering cable recovery, floater detachment and towing, and mooring line recovery. The model does not include anchor recovery, since it is assumed that removing anchors would disturb the biological

environment more than leaving them in place, and anchors are therefore assumed to remain on the seabed after end of operation.

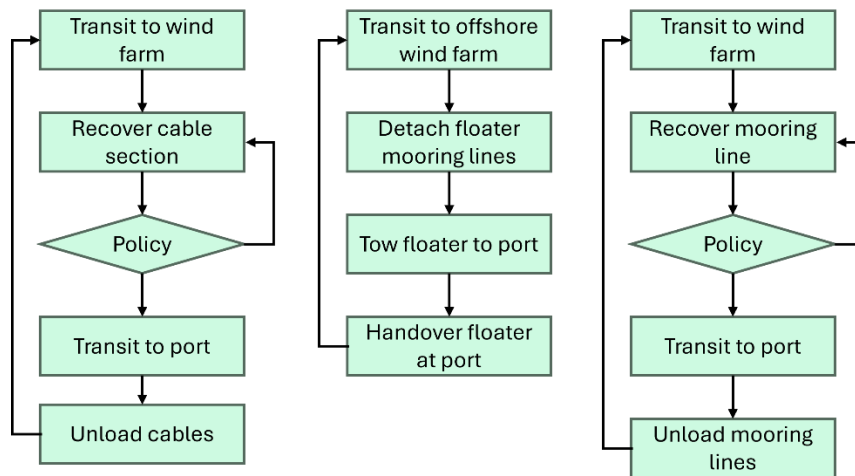


Figure 5: Decommissioning campaign case model in SeaSequence, showing the three subsystems for cable recovery, floater detachment and towing, and mooring line recovery.

Figure 5 shows the operation chains in the three decommissioning subsystems. The cable vessel transits to the wind farm, recovers cable sections, and returns to port to unload when needed before continuing until all cables are recovered. The towing vessel transits offshore, detaches the floater mooring lines, tows the floater to port for handover, and repeats until all floaters are recovered. The mooring line vessel transits offshore, recovers mooring lines, and returns to port to unload when needed before continuing until all mooring lines are recovered.

The subsystems are linked through dependency rules. In the decommissioning case, towing and detachment is only allowed to proceed after cable recovery has been completed, and mooring line recovery is only allowed to proceed after all floaters have been recovered.

3.2 OPEX modelling approach

Operations and maintenance costs (OPEX) arise throughout the wind farm's operational life and are associated with asset management and structural integrity. In this sense, the total OPEX can be divided into operational and maintenance costs (C_O and C_M). The flowchart in Figure 6 summarizes the methodology for estimating OPEX, highlighting the breakdown and interplay between operational and maintenance cost components.

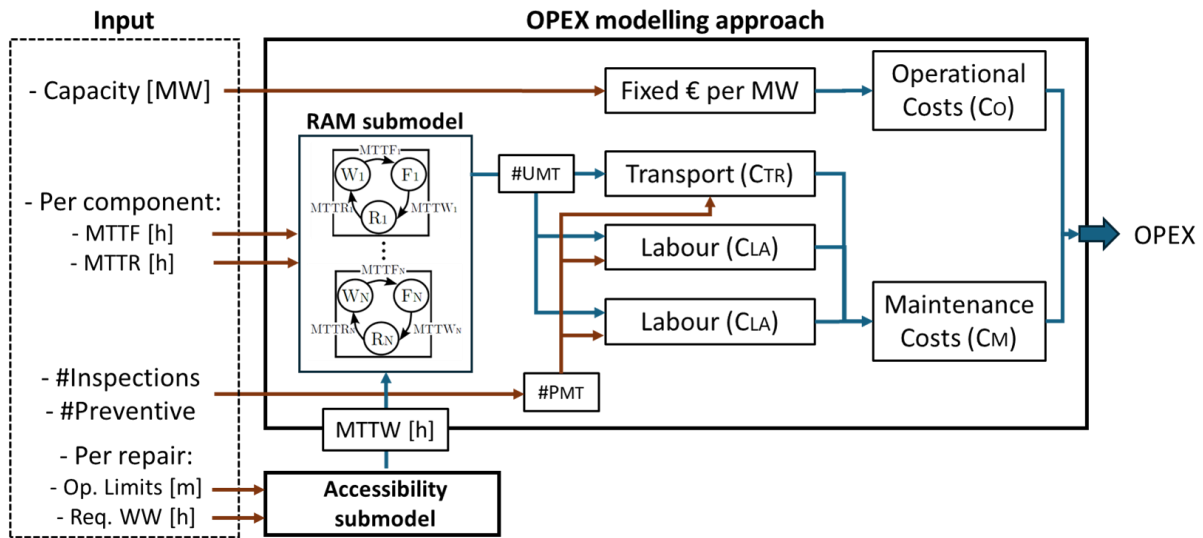


Figure 6: Overview of methodology for estimating OPEX

On one hand, expenses under C_O relate to the day-to-day running of the wind farm, covering site management, safety, control room, remote monitoring, transmissions charges, insurance and administrative services. The magnitude of these costs varies significantly from project to project. Accordingly, fixed operating costs are assumed at approximately \$31,000 per MW of installed capacity per year.⁷ Note that this operational cost is used as a benchmark and does not account for offshore site lease costs, which vary by country.

On the other hand, expenses under C_M correspond to all activities that ensure the continued operational integrity of the wind farm, including both planned routines (e.g., inspections and preventive servicing) and unplanned interventions (e.g., repairs and replacements). All maintenance activities require specialized transport means, technicians and materials. Accordingly, C_M can be defined as,

$$C_M = \sum_{t=1}^T \frac{C_{TR_t} + C_{LA_t} + C_{MA_t}}{(1+r)^t} \quad (4)$$

where C_{TR_t} is the cost of transport including mobilization, charter and fuel costs in year t , C_{LA_t} cost of labour in year t , and C_{MA_t} cost of materials used during maintenance activities including spare parts and components replaced as well as consumable used for repairs (e.g. lubricants and tools), in year t . For further details, see Centeno-Telleria et al. (2023)⁸.

The use of transport, technicians, and materials at the wind farm is directly linked to the frequency of required planned and unplanned maintenance activities. In the INF⁴INITY LCoE model, planned maintenance is specified in the input data, while unplanned maintenance is estimated using a probabilistic reliability, availability and maintainability (RAM) model. This probabilistic approach allows for a more realistic representation of operational behaviour and associated resource requirements over the wind farm's lifetime.

⁷ Hall, M., Lozon, E., Devoy McAuliffe, F., Baudino Bessone, M., Bayati, I., Bowie, M., Bozonnet, P., Castagné, M., Feng, J., Housner, S., Janocha, M., Jiang, Z., Kim, Y., Ko, D., Kölle, K., Lee, C., Lekkala, M.R., Liang, G., Mahfouz, M., Mohan, M., O'Connell D., Ong, M., Prieur, J., Rajasree, V., Schnepf, A., Snedker, T., Thurston-Keller, J., and Wright, C. The IEA Wind Task 49 Reference Floating Wind Array Design Basis. IEA Wind, 123 pp, 2024. DOI: 10.2172/2382797

⁸ Centeno-Telleria, M., Aizpurua, J.I., and Penalba, M. Computationally efficient analytical O&M model for strategic decision-making in offshore renewable energy systems. *Energy*, 285, 129374, 2023. DOI: 10.1016/j.energy.2023.129374



The RAM model evaluates the performance of the wind turbines in terms of their ability to function without failure (i.e., reliability), remaining operational over time (i.e., availability) and being restored to working condition efficiently after a failure (i.e., maintainability). Typically, probabilistic models are employed to capture the inherent uncertainties in failure and repair processes. Probabilistic models are developed to characterize both component-level and turbine-level performance.

A component-level continuous-time Markov chain model is used to represent the stochastic transitions among the working (W), failed (F) and repairing (R) states. The transition from W to F is governed by the mean time to failure ($MTTF$), the transition from F to R by the mean time to wait for a suitable weather window ($MTTW$) and the transition from R to W by the mean time to repair ($MTTR$), as detailed in Centeno-Telleria et al. (2023). In this regard, the total number of unplanned maintenance tasks for component i is defined as:

$$N_{MT} = \sum_{t=1}^T 8760 \cdot \left(\frac{1}{MTTF_t} \right) \cdot pr(W_t) \quad (5)$$

where 8760 is the number of hours in a year, T the total number of operational years, $MTTF_t$ the mean time to failure in year t , and $pr(W_t)$ the steady-state probability of being in state W_t defined as,

$$pr(W_t) = \frac{1}{(MTTF_t + MTTW_t + MTTR_t)} \quad (6)$$

where $MTTW_t$ is the mean time to wait for a weather window in year t and $MTTR_t$ the mean time to perform a repair in year t .

For estimating $MTTW_t$, the accessibility submodel is employed. The accessibility submodel estimates the $MTTW$ for performing a specific maintenance task. To do so, the metocean conditions at the site are considered. Additionally, the requirements of the maintenance task, in terms of operational limits and the duration of the required weather window, should be defined.

To evaluate different accessibility scenarios, a simulation-based approach is developed. This approach involves sampling metocean data over a specified period to replicate various potential time instants at which unplanned maintenance tasks may be required. For each sampled set of metocean conditions, the model identifies the first available weather window that satisfies the defined operational constraints and required weather window duration. By iterating over numerous samples, the model statistically estimates the $MTTW$ before the maintenance task can be safely executed, accounting for the variability of metocean conditions and the uncertainty associated with failure occurrence.

3.3 AEP modelling approach

The AEP modelling approach used in INF4INITY is based on the techno-economic framework previously developed by Sørensen and Larsen (2021)⁹. The primary objective of this framework is to facilitate preliminary production and cost assessments without requiring detailed technical specifications of the wind turbines or the precise layout of the wind farm. As a result, the model relies only on key inputs such as turbine characteristics (rotor diameter, hub height and rated capacity), wind farm scale (number of turbines and total area), site-specific Weibull parameters, water depths, and distances to the coast and nearest harbour (see Figure 7). The tool provides outputs including average annual power generation, power density (power per unit area), CAPEX, OPEX, and LCoE.

Inputs to the model are as follows:

- Wind turbine: Diameter, hub height and nameplate capacity

⁹ Sørensen, J.N. and Larsen, G.C. A minimalistic prediction model to determine energy production and costs of offshore wind farms. *Energies*, 14(2), 2021. DOI: 10.3390/en14020448



- Wind farm: Area of wind farm and number of wind turbines
- Wake model: Analytic “top-down” atmospheric boundary layer model
- Site data: Weibull parameters
- Cost model: Water depth, type of foundations and anchoring, distance to harbour

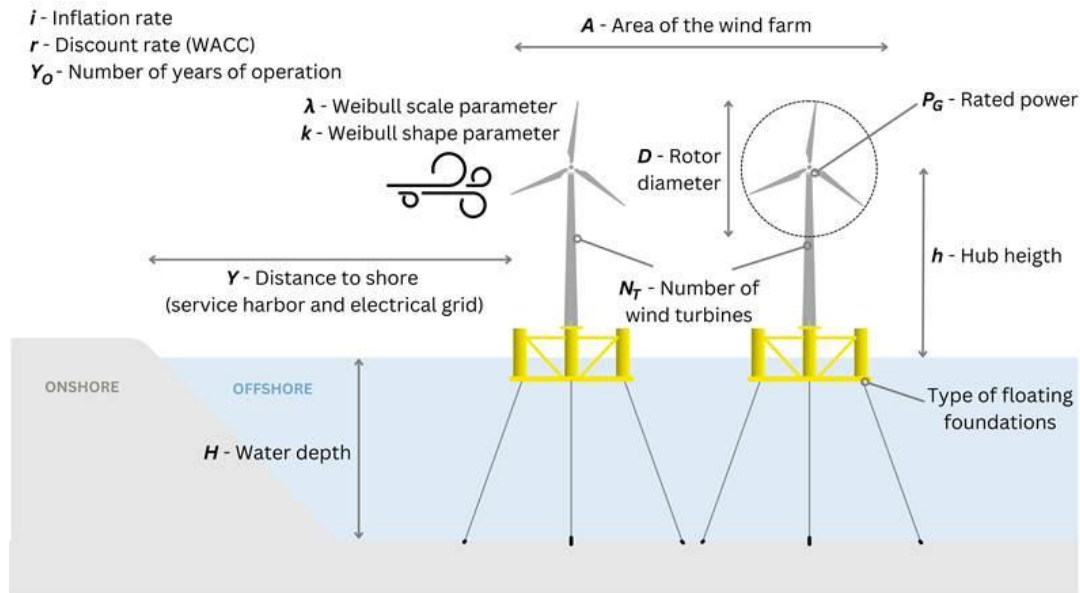


Figure 7: Scheme of the input parameters to the minimalistic model required for calculating energy production, CAPEX, OPEX, and LCoE.

The background for the AEP model is the atmospheric wind farm model developed by Frandsen (1992)¹⁰, which evaluates wake effects and their interaction with the atmospheric boundary layer. This model assumes that the wind farm is sufficiently large for the wind field within it to reach equilibrium with the surrounding atmospheric boundary layer (ABL) flow. A detailed explanation of the model, along with the derivations of its equations, can be found in Sørensen and Larsen (2021)⁹, where it is thoroughly described and validated against actual performance and cost data from several full-scale wind farms. Despite its simplicity, the model has demonstrated a remarkable ability to estimate both costs and power output for bottom-fixed offshore wind farms with high reliability¹¹. Recently, the cost model was extended to include simple expressions for floating wind turbine components¹². In the following paragraphs the various elements of the wind energy assessment model are presented. It is not the intention to go into details, but merely to present the main ideas and equations of the model. For more information, we refer to the paper by Sørensen and Larsen (2021)⁹, where all details are given.

The model treats the characteristics of the wind turbines in a simplified way using generic thrust and power curves that only depend on the installed power capacity (nameplate capacity) and the diameter of the rotors. Thus, specific details

¹⁰ Frandsen, S. On the wind speed reduction in the center of large clusters of wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics*, 39(1-3), 251–265, 1992. DOI: 10.1016/0167-6105(92)90551-K

¹¹ Sørensen, J.N., Garcia, A., Larsen, G.C., Pedersen, M.M. and Fournely, D. Extension and validation of minimalistic prediction model to determine the energy production of offshore wind farms. *Journal of Physics: Conference Series*, 2767, 2024. DOI: 10.1088/1742-6596/2767/9/092022

¹² Montes, A., Fournely, D., Sørensen, J.N. and Larsen, G.C. Techno-economic modelling of floating wind farms. *Energies*, 18(4), 967, 2025. DOI: 10.3390/en18040967.

of the wind turbines operating envelope, such as distributions of thrust and power coefficients as function of inflow wind speed, are not required. However, if they are known they can easily be incorporated in the calculations.

The generic power curve of a solitary wind turbine, $P = P(U)$, is at a given mean wind speed, U , below rated wind speed, approximated by the following generic expression:

$$P(U) = aU^3 + b \quad (7)$$

where the coefficients a and b are determined as:

$$a = \frac{P_G}{U_r^3 - U_{in}^3}, \quad (8)$$

$$b = \frac{P_G U_{in}^3}{U_r^3 - U_{in}^3}, \quad (9)$$

with P_G denoting the rated (installed) generator power, U_{in} is the cut-in wind speed and U_r is the rated wind speed.

The wind farm topology is defined only in terms of the total number of wind turbines, N_T , and the wind farm area, A . Denoting the assumed uniform distance between the wind turbines as L_T , the wind turbine interspacing, expressed in rotor diameters, is given as $S = L_T/D$. Assuming, as a simplifying approximation, that the wind farm is forms a square array, the following equation gives the interspacing as function of wind farm area and number of turbines:

$$S = \frac{\sqrt{A}}{D(\sqrt{N_T} - 1)} \quad (10)$$

As a first approximation, the model assumes that the wind farm is so large that the wind field inside the wind farm is in equilibrium with the ambient atmospheric boundary layer (ABL) flow field. The model relies on the following assumptions:

- The wind farm is large enough for the horizontally averaged, vertical wind profile to be horizontally homogeneous.
- The thrust on the wind turbine rotors is assumed to be concentrated at hub height.
- The horizontally averaged vertical wind profile is logarithmic both below and above hub height.
- The vertical wind profile is continuous.
- The height of the planetary boundary layer is considerably larger than the wind turbine's height.
- Turbulent wind speed fluctuations are horizontally homogeneous.

It is assumed that the wind turbines create two logarithmic boundary layers, matched at hub height by the shear forces exerted by the wind turbines on the flow. The model results in a simple analytic equation that determines the wake affected mean wind speed at hub height inside the wind farm. This equation depends on latitude, geostrophic wind speed, and the roughness length of the surface, which are all known parameters.

To determine the wind farm power production, and further to provide input to the applied cost model for wind farm O&M expenses, an estimate of the mean wind speed statistics both for the site without wind turbines (i.e. the ambient wind speed statistics) and for the internal wind farm flow field is needed. A two-parameter Weibull distribution is used to determine the average wind speed statistics over the year. The wind speed statistics inside a wind farm are, however, different from the wind speed statistics of the ambient undisturbed flow. To determine the average power production within the wind farm, the Weibull scale parameters need to be adjusted to the hub height of the turbines operating in the wind farm. For the detailed derivations, we refer to the original paper by Sørensen and Larsen (2021).

Since the above-described performance model essentially is based on a fully developed atmospheric boundary layer in equilibrium with an infinite wind farm, it is necessary to introduce a correction for the finiteness of a real wind farm. As a simple heuristic approximate expression for considering the finiteness of the farm, we use the following expression for the annual wind farm power production, P_E :



$$P_E = (1 - c)P_{WF,y} + cP_y, \quad (11)$$

where P_y is the ‘free-wind’ production, $P_{WF,y}$ is ‘wake-wind’ production, and c is a finiteness correction factor, $0 < c < 1$. The factor takes into account that the wind turbines at the edges of the wind farm are not subject to wake effects, some are subject to part wake effects, whereas others are subject to full wake effects. To determine c is calibrated against performance data from actual wind farms or computational high-fidelity results from e.g. Navier-Stokes simulations:

$$c(N_T, S, U) = \frac{P_{WF,y}(N_T, S, U) - P_y(U)}{P_E - P_y(U)}, \quad (12)$$

where S denotes the average distance between the turbines, measured in diameters, and U is the ambient undisturbed wind speed. To determine more precisely the c -parameter, we use the *Fuga* linear RANS model¹³. This was done by defining an ‘infinite’ reference wind farm consisting of a large number of wind turbines arranged in a square and by employing *Fuga* to compute the annual average power for different subsets of the farm, using various numbers of turbines, distances between the turbines and average wind speeds as input parameters. This was done by changing systematically these parameters, computing the total power production, as well as the power production inside the wind farm, and exploiting the above equation to determine the finiteness factor. Next, the outcome of this expanded in power function series of the wind speed, U , resulting in the generic equation $c(N_T, S, U)$. As a simplification, we exploit an approximate expression that does not depend on the wind speed:

$$c(N_T, S) = -0.045S + 1.611S^{1/4} - 0.966S^{1/8}N_T^{1/16}. \quad (13)$$

¹³ Ott S., Berg J. and Nielsen M. Linearised CFD models for wakes. Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. Denmark. Forskningscenter Risø. Risøe-R No. 1772, 2011.



4 The INF4INITY LCoE_e model

The traditional LCoE formula accounts for capital expenditure (CAPEX), operational and maintenance expenditure (OPEX), decommissioning expenditure (DECEX), annual production of energy (AEP) and a discount rate (r) which is evaluated over the expected lifetime of the project ($t = 1$ to T). The INF4INITY LCoE model and definitions and calculations of CAPEX, OPEX and DECEX were presented in Section 0.

An updated formula, enhanced LCoE model ($LCoE_e$) is proposed by INF4INITY to better include all relevant environmental and social costs on biodiversity and society. Environmental and social KPIs are included in the traditional LCoE formula by using a common language which aims to facilitate adoption and continued improvement:

$$LCoE_e = \frac{\text{Present value of all lifetime costs}}{\text{Present value of all lifetime energy outputs}} \quad (14)$$

$$LCoE_e = LCoE_{trad} + LCoE_{env} + LCoE_{soc} \quad (15)$$

In the above equation, $LCoE_{trad}$ is the traditional LCoE formula, $LCoE_{env}$ represents the environmental impact on the enhanced LCoE, and $LCoE_{soc}$ represents the social impact on the enhanced LCoE. A visual overview of the elements considered in the INF4INITY LCoE-e model is presented in Figure 8.

The environmental and social impacts on the enhanced LCoE may be both positive and negative. The different impacts are based on the environmental and social KPIs described in Sections 2.2.2 and 2.2.3. As for the calculation of the traditional LCoE, the calculations of $LCoE_{env}$ and $LCoE_{soc}$ are based on the KPIs impacts on CAPEX, OPEX and DECEX.

In the following, the environmental-enhanced LCoE aspects are outlined in Section 4.1, and the socio-enhanced LCoE aspects are outlined in Section 4.2.

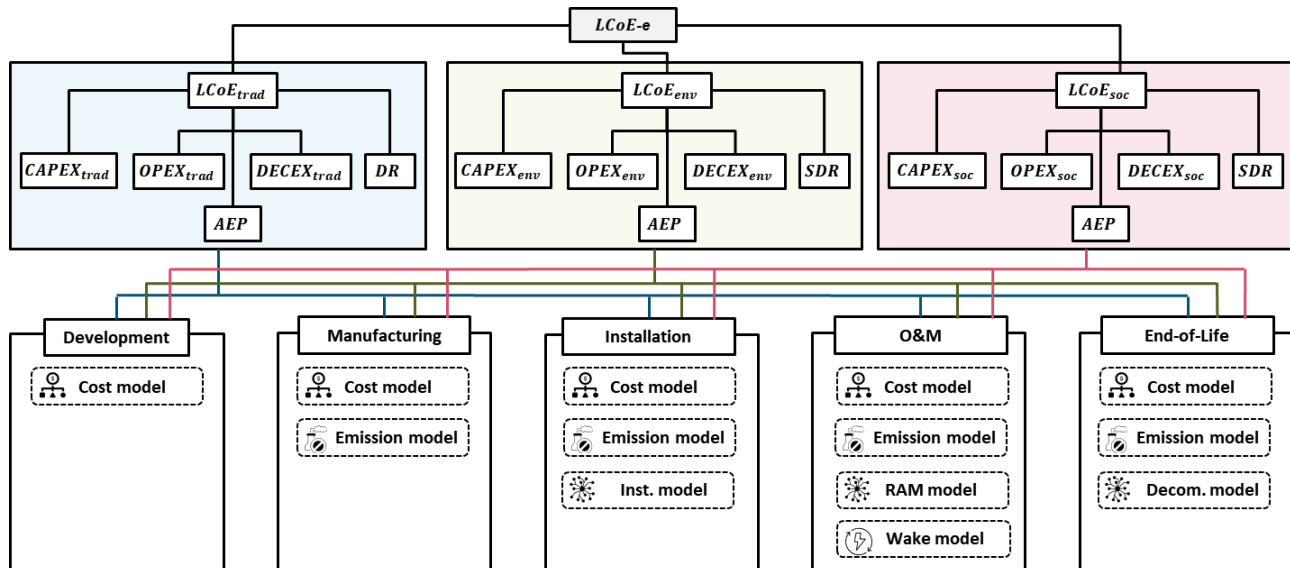


Figure 8: INF4INITY LCoE_e model - overview

4.1 Environmental-enhanced LCoE

The environmental costs and benefits (EC and EB) are included in the numerator of the equation of the $LCoE_{env}$. The EC- and EB-units are valued in different ways – see table below – and are multiplied by the differential of environmental

unit (EU) between the target and the reference project (ΔEU_t). The environmental costs and benefits can be included in the $LCoE_{env}$ as follows:

$$LCoE_{env} = \frac{CAPEX_{env} + \sum_{t=1}^T \frac{OPEX_{env,t}}{(1+sdr)^t} + \frac{DECEX_{env}}{(1+sdr)^T} + \frac{(\Delta EU_t) * EC_t}{(1+sdr)^t} + \frac{(\Delta EU_t) * EB_t}{(1+sdr)^t}}{\sum_{t=1}^T \frac{AEP_t}{(1+sdr)^t}} \quad (16)$$

The Social Discount Rate (SDR) is applied when the environmental costs and benefits are included in the enhanced LCoE model as it represents society's time preferences when it comes to costs and benefits now and in the future as well as a risk-premium reflecting society's preferences for systematic risks and uncertainties.

In the following table the environmental KPIs presented in previous chapters, which represent the environmental costs and benefits are listed. All the environmental are linked to the $LCoE_e$ and for each of them a target unit is suggested.

Table 2: Environmental KPIs and their link to $LCoE_{env}$.

Environmental KPI	Value type					Target unit
	Non-price criteria	CAPEX _{env}	OPEX _{env}	DECEX _{env}	LCoE _e	
KPI E1 – Avoided GHG emissions					X	€/ton CO ₂ -e
KPI E2 – Additional carbon uptake					X	€/ton CO ₂ -e
KPI E3 – Release of sequestered carbon					X	€/ton CO ₂ -e
KPI E4 – GHG-emissions from fossil-based activities					X	€/ton CO ₂ -e
KPI E5 – Increased nutrient load					X	€/ton nutrient
KPI E6 – Removal of nutrients					X	€/ton nutrient
KPI E7 – Release of chemicals and other pollutants					X	€/ton pollutant
KPI E8 – Uptake and possible removal of chemicals and pollutants					X	€/ton pollutant
KPI E9 – Protection of benthic vegetation					X	€/km ²
KPI E10 – Protection of benthic fauna					X	€/km ²
KPI E11 – Increased (or decreased) diversity in flora and fauna					X	€/[biological unit]
KPI E12 – More (or less) rare and protected species					X	€/[biological unit]
KPI E13 – Changes in commercial species					X	€/ton [species]
KPI E14 – More (or less) invasive species					X	€/ton [species]
KPI E15 – (Adverse) Visual impacts of the offshore installations					X	€/km [distance]
KPI E16 – Noise pollution during construction, operation and decommissioning					X	€/dB [threshold]
KPI E17 – Changes in air quality during construction and decommissioning					X	€/PM _{2.5} etc.
KPI E18 – Reduction of the human use value					X	€/km ² or MW

As all environmental KPIs are part of the $LCoE_e$ the target units are not directly related to the monetary value of CAPEX, OPEX or DECEX but rather to various other units:

- **GHG-emissions and carbon uptake:** KPIs E1-4 are all measured in ton CO₂-equivalents. Often the cost of carbon used is equivalent to the carbon price from the EU Emissions Trading System market. This price reflects the marginal cost of reducing carbon emissions in the energy and emissions-intensive sectors and hence it is the opportunity cost of emitting an extra ton of carbon. However, alternatively the social cost of carbon (SCC) can be used in the assessment of GHG-emissions and carbon uptake (see section 2.2.3.3), which for the purposes of the $LCoE_e$ -model is more appropriate than the EU-ETS-carbon price.
- **Nutrient loads and uptake:** KPIs E5-6 are measured in ton of nutrients e.g. nitrogen or phosphorous etc. depending on the type of emissions. As for GHG-emissions the price or value of nutrient loads or uptake is usually determined based on the marginal cost of reducing nutrient leakage in the relevant sectors e.g. agriculture or sewage treatment.
- **Pollutant release, uptake and removal:** The target units of KPIs E7-8 depend on the pollutant or chemical and the exact damage cost of that pollutant. The environmental damages caused by some pollutants and chemicals are well-known whereas others are more uncertain. Again the price or value is often based on the marginal cost of reductions but for some are the damage costs estimated. It must be noted that critical pollution is most often avoided through a comprehensive environmental impacts assessment process (EIA) and therefore environmental damages are significantly reduced.
- **Protection of species:** When it comes to the protection of vegetation and fauna and KPIs E9-10 the value is often directly related to the size of the protected marine area. The value of the protection (from human interference) however depends on the species in question, their protection status and perceived value of these species to society. Flagship-species such as sea mammals e.g. dolphins, whales, seals and sea lions are valuable to humans and that will be reflected in most valuation studies of these species. Contrary to this the value of other species that are less favoured by humans are low in similar valuation studies and the intrinsic value of a protected area as a whole must be considered.
- **Biodiversity and abundance:** KPIs E11-12 reflects the diversity and abundance of flora, fauna, rare and protected species. For the relevant marine area the appropriate biological units must be established and linked to a price or value based on an avoided cost approach or benefit-transfer from relevant valuation studies.
- **Changes in species:** KPIs E13-14 related to commercial and invasive species are valued using the commercial landing values of fish etc. and the alternative costs of removing the invasive species in question.
- **Visual impacts:** The adverse visual impacts of offshore wind farms (KPI E15) depend on the distance from shore and the size of the population affected by the visual impacts. Wind turbines more than 35-40 kilometres offshore are usually not visible to the naked human eye and the visual impacts are therefore negligible. In several valuation studies the visual impacts of offshore wind turbines have been assessed using different valuation techniques including stated preference methods and hedonic pricing methods (e.g. house pricing methods). Using the abovementioned distance as a threshold and the parameters and conclusions from valuation studies of other offshore wind farms.
- **Noise and air pollution:** As for chemical pollutants (KPIs E7-8), noise and air pollution (KPIs E16-17) is most often avoided through a comprehensive environmental impacts assessment process (EIA), which reduces the environmental damages significantly. However, noise disturbance above certain thresholds can lead to disturbance of animals and humans and the same goes for air pollutants such as particulate matter, nitrous oxides etc.
- **Reduction of human use values:** Introduced limitations to human activities (KPI E18) is often related to the area of the offshore wind farm and the value of that area to humans can be related to both commercial and recreational activities. The commercial activities are reflected in the value of fisheries or aquaculture (see KPIs E13-14) and the recreational activities are reflected in the value of tourism in the area and adjacent areas. The valuation of tourism and recreational use is often assessed in studies using the travel-cost method to reveal preferences and use values to humans. In some cases, the developer pays compensation to the users who have had their access restricted by



the wind farm. Such colocation compensation to sea users and community benefit-sharing schemes is often related to the MW-capacity of the farm and not dependent on the area of the offshore wind farm as such.

4.1.1 Biodiversity and abundance effects

KPIs E11-12 related to the diversity and abundance of flora, fauna, rare and protected species are of particular interest when it comes to nature inclusive designs (NIDs). Consequently, these effects are explored and summarized in the following sections.

4.1.1.1 Mitigative biomass production

The production of biomass at the offshore wind farms could contribute to the mitigation of the overall impact of floating offshore wind farms, through nutrient and CO₂ retention. Recently, stimulating marine biomass production has been applied in an attempt to mitigate the effect of eutrophication in coastal waters, through retention of nutrients. The potential yield of marine biomass production is highly variable depending on the species in question and environmental factors such as salinity, temperature, and availability of light and nutrients for algae and food items such as mussels. Cultivation of larger species of macroalgae such as sugar kelp (*Saccharina latissima*) has been attempted with varying results, in general providing a low yield (Bruhn et al., 2016)¹⁴ Mussels such as blue mussels, oysters and carpet mussels, are being cultivated at large scale producing low emission protein for food and livestock feed, and is making up roughly a third of the aquaculture production within the European Union (Avdelas et al., 2021)¹⁵. The European production is in decline though, primarily due to a decrease in market prices i.e. demand.

The application of biomass production installations can potentially affect the balance and water flow patterns around floating offshore wind turbine foundations. Increasing drag and wear on the mooring connection between the floating wind turbine foundation and the gravity anchor, thus affecting the productivity of the wind turbine.

The potential benefits of applying biomass production as a mitigating measure in floating offshore wind farms are outweighed by technical constraints, monetary cost and emissions related to transport to and from the offshore sites. As a result, it is not seen as a viable option.

4.1.1.2 Effect on habitats and species

The construction of offshore wind farms with related artificial structures have been found to have varying impact on the marine nature and habitats (Degraer et al., 2020)¹⁶. The introduction of an artificial structure can have a negative effect on patterns in biological communities through the removal or disturbance of existing habitats that are covered or damaged by the new constructions such as foundations, gravity anchors, mooring and scour protection etc. The direct impact of such structures is attributed to the area affected by the overall footprint by bottom structures on the sea floor. Floating foundations as applied in this study are generally considered to have a low impact on sea floor.

¹⁴ Bruhn, A., Tørring, D.B., Thomsen, M., Canal-Vergés, P., Nielsen, M.M., Rasmussen, M.B., Eybye, K.L., Larsen, M.M., Balsby, T.J.S. and Petersen, J.K. Impact of environmental conditions on biomass yield, quality, and bio-mitigation capacity of *Saccharina latissima*. *Aquaculture Environment Interactions*, 8, 619-636, 2016. DOI: 10.3354/aei00200

¹⁵ Avdelas, L., Avdic-Mravljje, E., Borges Marques, A.C., Cano, S., Capelle, J.J., Carvalho, N., Cozzolino, M., Dennis, J., Ellis, T., Fernández Polanco, J.M., Guillen, J., Lasner, T., Le Bihan, V., Llorente, I., Mol, A., Nicheva, S., Nielsen, R., van Oostenbrugge, H., Villasante, S., Visnic, S., Zhelev, K. and Asche, F. The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities. *Reviews in Aquaculture*, 13, 91-118, 2021. DOI: 10.1111/raq.12465

¹⁶ Degraer, S., D.A. Carey, D.A., Coolen, J.W.P., Hutchison, Z.L., Kerckhof, F., Rumes, B. and Vanaverbeke, J. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. *Oceanography*, 33(4), 48-57, 2020. DOI: 10.5670/oceanog.2020.405



The effects of OWF's are not known solely to have a negative impact on marine habitats and species. Studies on the long-term effects of OWFs (e.g. Horwath et al., 2020¹⁷ and Clubley et al., 2026¹⁸) have concluded that in some cases these can contribute positively through:

1. **Habitat Creation** – Turbine foundations and associated structures act as artificial reefs, increasing the structural heterogeneity of benthic habitats.
2. **Biodiversity Enhancement** – Introduced habitats can attract fish, seabirds, and marine mammals, potentially increasing local biodiversity.
3. **Fisheries** – Structures may serve as nurseries or feeding grounds for commercially important fish species.

4.1.1.3 Protection of vulnerable habitats and species

Not all habitats and species will respond positively to alterations in the environment but can be highly sensitive to disturbances from human activities at sea. A number of these are protected through the implementation of EU directives such as the Habitat and Birds Directives and international and regional conventions like the Ramsar, Helsinki Convention, OSPAR and Barcelona Conventions and consolidated through national legislations.

In order to protect vulnerable species and habitats a network of Marine Protected Areas (MPA's) have been designated throughout the European seas, regulating activities that can have a negative impact on the species and habitats, they are designated to protect.

4.1.1.4 Other Effective Conservation Measures

In addition to the network of MPA's there are other areas that can act as a refuge for vulnerable species and habitats. These are geographically defined areas not designated as protected areas but managed in ways that provide effects like that of MPA's, by excluding activities that have a negative impact on marine life. These areas are referred to as Other Effective Conservation Measures (OECMs).

As an example, certain fisheries can have a negative effect on species and habitats as bottom dragging gear such as trawl can disturb benthic habitats, and gillnetting can lead to potential bycatch of nontarget species such as birds or marine mammals. Marine traffic in general, including that of fishing vessels, is well known to affect a number of marine animals by visual disturbance and noise pollution. Commercial fisheries and other marine traffic are generally excluded from the area occupied by an OWF. This will eliminate related impacts on the marine life in that area, making it a potential OECM.

Consequently, it is recommended to focus on the ability of NIDs to further secure and enhance any potential ecosystem services provided by the OWFs with emphasis on their role as OECMs adapted to regional characteristics and vulnerable species and habitats as designated in the afore mentioned directives and regional conventions.

¹⁷ Horwath, S., Hassrick, J., Grismala, R. and Diller, E. Comparison of environmental effects from different offshore wind turbine foundations. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA, OCS Study BOEM 2020-041, 42 pp, 2020. <https://www.boem.gov/sites/default/files/documents/environment/Wind-Turbine-Foundations-White%20Paper-Final-White-Paper.pdf>

¹⁸ Clubley, C.H., Mohn, C., Larsen, J., Schourup-Kristensen, V., Ishimwe, A.P., Møller, E.F., Dahl K. and Maar, M. Cumulative effects of offshore wind farms on dispersal corridors for non-indigenous species and ecosystem indicators. Aarhus University, DCE – Danish Centre for Environment and Energy, 73 pp, 2026. https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Videnskabelige_rapporter_600-699/SR688.pdf



4.2 Socio-enhanced LCoE

Table 3 summarises social KPI defined in section 2.2.3. It outlines the relationship between each indicator and the enhanced LCoE framework identifying the mechanisms through the socioeconomic assessment of NIDs.

For each KPI, the table specifies:

- Non-price criteria: increasingly reflected in recent offshore wind tendering processes and regulatory frameworks;
- Contributor to social capital expenditure ($CAPEX_{soc}$);
- Contributor to social operational expenditure ($OPEX_{soc}$);
- Contributor to social decommissioning expenditure ($DECEX_{soc}$); or
- An enhanced LCoE economic factor which directly modifies the structure of the LCoE traditional equation.

The table also targets the unit associated to each indicator to support future quantification and modelling. Most monetizable social indicators are expressed in €/MW or €/MW-year, facilitating their integration into project cost structures.

The classification further highlights that not all indicators influence the enhanced LCoE framework. Some of them act primarily as non-price criteria shaping project acceptability and alignment with tender requirements, however, do not affect the LCoE cashflow.

Table 3: Classification of the social KPIs considered within the enhanced LCoE framework

Social KPI	Value type					Target unit
	Non-price criteria	CAPEX _{soc}	OPEX _{soc}	DECEX _{soc}	LCoE _e	
Social Acceptance and Licence to Operate						
KPI S1 – Place Attachment	N	X	-	-	-	€/MW
KPI S2 – Cultural landscapes	-	X	-	-	-	€/MW
KPI S3 – Environmental impact perception	N	X	-	-	-	€/MW
KPI S4 – Technology Acceptance (NIDs)	-	X	X	-	-	€/MW
KPI S5 – Community Benefit Schemes	N	-	X	-	-	€/MW
KPI S6 – Community Ownership	N	-	X	-	-	€/MW
KPI S7 – Community Trust and Engagement	N	X	X	-	-	€/MW
Regional Economic Development						
KPI S8 – Labour Inclusivity (Vulnerable Groups)	N	X	X	-	-	€/MW
KPI S9 – Training and Employment of Apprentices	N	X	X	X	-	€/MW
KPI S10 – Co-location and Sea-Use Interactions	N	X	-	-	-	€/MW
KPI S11 – Employment	N	-	-	-	-	€/MW
KPI S12 – Local Small and Medium Enterprise (SME) Engagement	N	-	-	-	-	€/MW
Social Macroeconomics						
Social Cost of Carbon (SCC)	-	-	-	-	X	€/ton CO ₂ -Eq
Social Discount Rate (SDR)	-	-	-	-	X	[%/yr]

Value type features:

- Non-price criteria are those that are requested in the most up to date tendering processes, which may or may not influence an LCoE_e. Non-price criteria included in recent tendering processes may result in a redistribution of CAPEX, OPEX or DECEX costs. If redistribution of costs exists, but the overall cost figure does not increase nor decrease, these are not to be considered in the LCoE_e. Non-price criteria do not modify the enhanced LCoE equation itself. Nonetheless, a non-blind approach is essential to be aligned to current social and regulatory standards and future potential LCoE_e considerations.
- CAPEX_{soc} represents all capital expenditure costs related to social KPIs, which contribute to the CAPEX_e.
- OPEX_{soc} represents all operation and maintenance costs related to social KPIs, which contribute to the OPEX_e.
- DECEX_{soc} represents all decommissioning costs related to social KPIs, which contribute to the DECEX_e.
- LCoE_e factors refer to those that add-up to the equation structure itself.

CAPEX_{soc}, OPEX_{soc} and DECEX_{soc} act through the traditional cost structure of the project increasing or decreasing expenditure, whilst specific LCoE_e economic factors such as social carbon costs and social discount Rate, are shaping the LCoE_e equation in the following manner.

Social cost of carbon (SCC): it is included through a formula embedded as a sum in the numerator of the numerator factor in the equation of LCoE_e. SCC is measured in €/ton which are multiplied by the differential of LCA between the target and the reference project. SCC value has been studied broadly, and reference numbers are available and are constantly updated. Figures may differ greatly depending on the methodology used. The KPI SCC would be included in the LCoE_e as follows:

$$LCoE_e = \frac{CAPEX + \sum_{t=1}^T \frac{OPEX_t}{(1+r)^t} + \frac{DECEX}{(1+r)^T} + \frac{(\Delta LCA_t) * SCC_t}{(1+r)^t}}{\sum_{t=1}^T \frac{AEP_t}{(1+r)^t}} \quad (17)$$

Social discount rate (SDR): The KPI SDR would be included as a replacement to the financial discount rate in the LCoE_e as follows:

$$LCoE_e = \frac{CAPEX + \sum_{t=1}^T \frac{OPEX_t}{(1+sd_r)^t} + \frac{DECEX}{(1+sd_r)^T}}{\sum_{t=1}^T \frac{AEP_t}{(1+sd_r)^t}} \quad (18)$$

For the LCoE_e model in the INF4INITY project, the financial discount rate is used when calculating the traditional LCoE (LCoE_{trad}), while SDR is used for the environmental and social considerations (LCoE_{env} and LCoE_{soc}).



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This report is currently under review by CINEA. Its contents are provisional and may be subject to change following the review process.

5 Case study presentation

This section provides a comprehensive description of the case study used for the sensitivity analysis: a 1,005 MW floating offshore wind farm based on 67 turbines of 15 MW each, sited at a representative deep-water North Sea location. The case study is designed to be technically coherent, while remaining a generic reference farm rather than a site-specific commercial project.

5.1 Project overview

The farm is a 1 GW-class deployment, a scale representative of future commercial floating wind projects in zones such as the North Sea. The 67-turbine configuration was selected to achieve a round-number capacity close to 1,000 MW while respecting the 15 MW rated power of the selected turbine class. A 25-year operational lifetime is assumed, consistent with current design standards for offshore wind structures and the financial assumptions used by major floating wind developers. The following table summarises the top-level project parameters.

Table 4: Top-level project parameters

Parameter	Value
Farm coordinates	59.00° N, 2.00° W
Number of turbines	67
Turbine rated capacity	15 MW
Total installed capacity	1,005 MW
Project start (development)	2025
Manufacturing start	2028
Installation year	2030
First power (start of operation)	2031
End of operational life	2055
Decommissioning year	2056
Total project duration	31 years
Site water depth	100 m
Port	Port of Nigg
Distance to port	190 km
Distance to shore	50 km
Power price (real, 2025 €)	65 €/MWh



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Financial discount rate (WACC)	8%/yr
Social discount rate (SDR)	3.5%/yr
Inflation rate	2.5%/yr

5.2 Farm layout and array configuration

The site selected for this study is in the Scottish Sea and has been chosen based on the outcomes and criteria established in a previous project deliverable in INF⁴INITY (D5.2¹⁹), which assessed suitability in terms of environmental conditions, feasibility and overall project constraints. The wind farm consists of 67 turbines, each rated at 15 MW, located approximately 50 km from shore in water depths of approximately 100 m. Furthermore, the farm layout implemented in this work is also defined from deliverable D5.2, maintaining consistency with earlier design assumptions, spatial configuration and optimisation considerations.

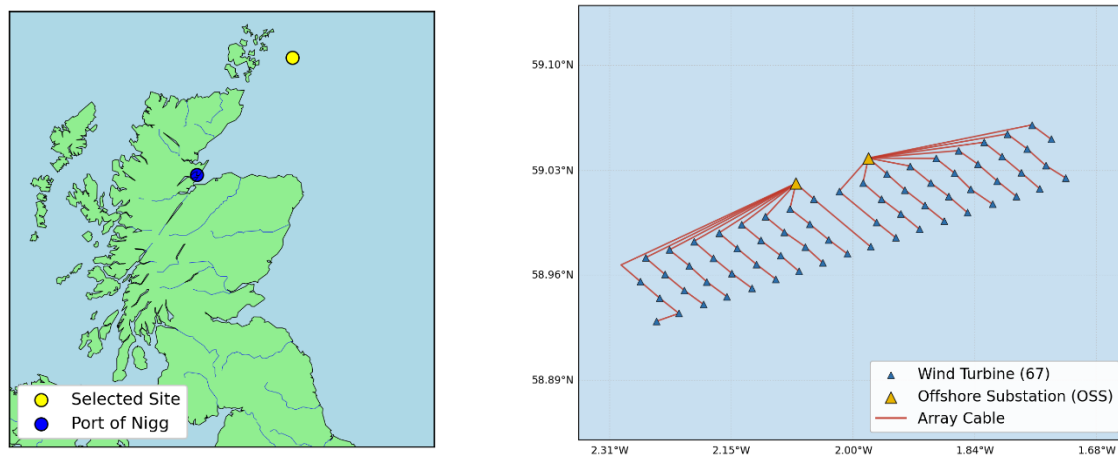


Figure 9: Port, site location and wind farm layout

The 67 turbines are arranged in an irregular array optimised to balance energy yield, inter-array cable length and wake interactions. The inter-array cable system consists of 18 radial strings (feeder cables) connecting groups of approximately 3–4 turbines each to the offshore substation. Average string length is 5.5 km, resulting in a total inter-array cable length of approximately 100 km. The table below summarises the farm layout parameters. The following table summarises the farm layout parameters

Table 5: Wind farm layout parameters

Farm Layout Parameter	Value
Total turbines	67
Bounding-box area	~480 km ²

¹⁹ INF⁴INITY D5.2: <https://inf4inity.com/wp-content/uploads/2025/01/D5.2-Farm-Layout.pdf>

Average nearest-neighbour spacing	1.78 km (7.4 × rotor diameter)
Dominant array row orientation	NW–SE (perpendicular to prevailing SW wind)

5.3 Metocean conditions

The metocean conditions applied in the analysis are derived from a previous project deliverable²⁰ that provides site-specific design load cases for floating offshore wind turbine applications using historical datasets, ensuring that the environmental inputs are robust, representative and aligned with long-term observations. The dataset spans 1995–2020 at hourly resolution, providing 25 years of significant wave height, wind speed and direction at 100 m above mean sea level. These time series are used directly to compute annual energy production via the turbine power curve, and to determine operational weather windows constraining vessel access and operations’ scheduling throughout the project lifecycle.

5.4 Turbine technology

The turbine modelled is representative of the IEA 15 MW offshore reference turbine²¹. With a 240 m rotor diameter and 150 m hub height, it is designed to maximise energy capture at the moderate-to-high wind speeds characteristic of deep-water North Sea sites, while maintaining structural feasibility for floating platforms. The following table summarises the indicative turbine mass breakdown and principal material composition adopted for the assessment. Material compositions represent first-order approximations adopted for emission intensity calculations, not detailed bill-of-materials breakdowns²². Each component is allocated to primary structural materials; minor constituents, carbon fibre in blades, and other uncharacterised fractions are excluded as a conservative simplification.

Table 6: Turbine mass breakdown and principal material composition

Component	Mass (per turbine)	Total (67 turbines)	Primary Material Composition (approximation)
Blades (65 t × 3)	195 t	13,065 t	Glass fibre (45%) + epoxy (30%)
Nacelle (excl. generator & hub)	258 t	17,286 t	Steel (60%) + copper (3%)
Generator & hub	372 t	24,924 t	Steel (55%) + copper (5%)
Tower	860 t	57,620 t	Steel (100%)

²⁰ Metocean data: <https://doi.org/10.24355/dbbs.084-202407250914-0>

²¹ Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C. and Viselli, A. Definition of the IEA 15-megawatt offshore reference wind turbine. 2020. <https://docs.nlr.gov/docs/fy20osti/75698.pdf>

²² Allekotte, L. and Garrett, P. Life Cycle Assessment of electricity production from an offshore V236-15 MW™ wind plant. Vestas Wind Systems A/S, 124 pp, 2024.

<https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/environment/LCA%20of%20Electricity%20Production%20from%20an%20offshore%20V236-15MW.pdf.coredownload.inline.pdf>



Total	≈1,685 t	≈112,895 t	
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5.5 Floating substructure

The floating substructure considered in this study is a tension leg platform (TLP) designed by GICON as part of the INF⁴INiTY project, with a total mass of 8,000 t per unit. For cost and emissions modelling purposes, the platform material composition is characterised as a first-order approximation, resulting in a combined steel-related fraction of approximately 85% of the total system mass. The remaining 15% corresponds to operational ballast, coatings, auxiliary systems and other uncharacterised material.

Table 7: Characteristics of the floating substructure

Platform Parameter	Value
Platform type	TLP
Total platform mass	8,000 t per unit
Steel fraction	85%
Others (operational ballast, coating, auxiliary system, etc.,) fraction	15%
Steel unit cost	€0.903/kg

5.6 Mooring and anchors

Each floating unit is held in position by eight Aramid tendons (two at each corner of the floater) connected to the four hybrid anchors installed in the seabed as taut-mooring. As a TLP, station-keeping is achieved through excess buoyancy restrained by the tendons in tension, which resist both vertical uplift and horizontal environmental loads from wind, waves, and current. Tendon length is approximated ≈47 m per tendon at the 100 m reference site. The following table summarises the main characteristics of mooring and anchors.

Table 8: Characteristics of mooring and anchors

Parameter	Value
Tendon configuration	8 vertical tendons per unit
Tendon unit weight	65 kg/m
One Tendon length at 100 m depth	~47 m
Tendon material cost	€25-35/kg
Total tendon mass per turbine	~24.5 t
Anchors per turbine	4



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Hybrid anchor mass	4,000 t per anchor
Concrete fraction	30%
Ballast (stone or similar) fraction	60%
Steel	10%

5.7 Electrical infrastructure

The electrical infrastructure connects the 67 floating turbines to the onshore grid through three sequential components: a dynamic inter-array cable network collecting power across the array, an offshore substation stepping up voltage for efficient transmission, and a high-voltage export cable delivering power to shore over approximately 50 km. The main parameters and cost assumptions adopted for each component are summarised in the following table^{23,24}.

Table 9: Main parameters and cost assumptions for electrical components

Electrical Component	Parameter	Value
Inter-array cables	Number of cable strings	18
	Average length per string	5.5 km
	Total inter-array cable length	≈100 km
	Unit cable cost	€614/m (dynamic cable)
	Buoyancy modules (per cable)	€128,000
	Bend stiffeners (per cable)	€235,000
	Total cable cost	≈€60.8 M (cable only)
	Total accessories cost	≈€6.5 M (18 × €363k)
Offshore substation (OSS)	Cost	€300k/MW
	Installation cost	60k€/MW
Export cable	Length	≈50 km (shore distance)
	Unit cost	€234k/MW

²³ BVG Associates. Guide to a Floating Offshore Wind Farm. 2025 <https://guidetofloatingoffshorewind.com/>

²⁴ Hall, M., Lozon, E., Devoy McAuliffe, F., Baudino Bessone, M., Bayati, I., Bowie, M., Bozonnet, P., Castagné, M., Feng, J., Housner, S., Janocha, M., Jiang, Z., Kim, Y., Ko, D., Kölle, K., Lee, C., Lekkala, M.R., Liang, G., Mahfouz, M., Mohan, M., O'Connell D., Ong, M., Prieur, J., Rajasree, V., Schnepf, A., Snedker, T., Thurston-Keller, J. and Wright, C. The IEA Wind Task 49 Reference Floating Wind Array Design Basis. IEA Wind, 123 pp, 2024. DOI: 10.2172/2382797



	Cable accessories	€29.25k/MW
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5.8 Marine logistics and vessel fleet

Marine operations across all project phases are coordinated from a single marshalling port located 50 km from the farm centre. Transit time to site governs weather-window utilisation and is therefore a primary driver of both installation duration and O&M cost. Two distinct vessel fleets are employed. The installation and decommissioning fleet execute the one-off offshore campaigns at either end of the project life: anchor deployment, mooring installation, platform tow-out and inter-array cable laying during construction, with the reverse sequence at decommissioning. The O&M fleet supports continuous maintenance throughout the 25-year operational life, ranging from routine crew transfers for minor interventions to heavy-lift operations for major component replacements. The Cable Laying Vessel (CLV) serves a dual role, mobilising for inter-array cable installation during construction and again for array cable replacement events during operations. All other vessels are dedicated to a single fleet. Vessel day rates and mobilisation costs used in the economic model are summarised in the following table^{25,26}.

Table 10: Vessel day rates and mobilisation cost

Vessel Type	Role	Day Rate	Mobilisation
Anchor-handling vessel (AHV)	Anchor installation	€80,000/day	€500,000
Mooring installation vessel	Mooring line deployment and tensioning	€75,000/day	€500,000
Towing vessel (tug)	Platform tow-out from assembly port to site	€70,000/day	€400,000
Cable lay vessel (CLV)	Inter-array and export cable installation	€75,000/day	€500,000
Crew transfer vessel (CTV)	Manual resets, minor/medium repairs, annual service	€1,750/day	0
Field support vessel (FSV)	Major repairs (multi-day, crew accommodation)	€9,500/day	0
Heavy lift vessel (HLV)	Major component replacement	€150,000/day	€500,000

²⁵ Dinwoodie, I., Endrerud, O.E.V., Hofmann, M., Martin, R. and Sperstad, I.B. Reference cases for verification of operation and maintenance simulation models for offshore wind farms. *Wind Engineering*, 39(1), 1-14, 2015. DOI: 10.1260/0309-524X.39.1.1

²⁶ Centeno-Telleria, M., Yue, H., Carrol, J., Aizpurua, J.I. and Penalba, M. O&M-aware techno-economic assessment for floating offshore wind farms: A geospatial evaluation off the North Sea and the Iberian Peninsula. *Applied Energy*, 371, 123684, 2024. DOI: 10.1016/j.apenergy.2024.123684

5.9 Installation phase

The offshore installation campaign follows four sequential operations, each constrained by dedicated operational limits, as shown in the following table:

Table 11: Data for offshore installation campaign

Operation	Vessels	Wave limit	Wind limit	Weather window	Duration
Anchor installation	AHV	2.5 m	15 m/s	6 h	4 h/anchor
Mooring line deployment & tensioning	Mooring vessel	2.5 m	15 m/s	6 h	4 h/line
Platform tow-out to site	Towing vessel	3.0 m	20 m/s	12 h	8 h/floater
Inter-array cable laying	CLV	2.0 m	12 m/s	6 h	6 h/section

For the installation of 67 turbines, this represents 268 anchors, 268 mooring lines, 67 floaters and 18 cable sections. The AHV carries 10 anchors per trip, the mooring vessel 10 lines per trip and the CLV 5 cable sections per trip. All vessels transit from the port 50 km from the farm centre. On the other hand, the installation cost is estimated in two parts. The first is the direct vessel cost computed by the simulation in SeaSequence: time-charter day rates applied over the simulated campaign duration, plus one-off mobilisation costs for each vessel. The second is a set of parametric cost items not captured by the vessel simulation, derived from BVG Associates industry benchmarks²³.

5.10 Operations and maintenance phase

Eight distinct maintenance task types are defined (Table 12), spanning brief manual resets to full major component replacements. Each task is characterised by its mean time between failures (MTBF), repair duration, direct material and labour cost, assigned vessel type, and weather-window constraints expressed as maximum significant wave height (Hs) and wind speed. All vessels operate from a port located 50 km from the farm. In addition to these task-triggered costs, a fixed operational expenditure of €50,000/MW/year covers insurance, lease, and monitoring, and a crew of 20 resident technicians is costed at €80,000/person/year²⁵.

Table 12: Maintenance tasks and characteristics

Task Type	MTBF (hours)	Frequency per turbine/yr	Repair Duration (hrs)	Direct Cost (€)	Vessel	Hs limit (m)
Manual reset	1,168	7.50	3	0	CTV	1.5
Minor repair	2,920	3.00	7.5	2,500	CTV	1.5
Medium repair	31,854	0.275	22	25,000	CTV	1.5



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Major repair	219,000	0.040	26	75,000	FSV	2
Major replacement	109,500	0.080	52	350,000	HLV	1.5
Annual service	8,760	1.00	60	200,000	CTV	1.5
Floater minor failure	131,138	0.067	8	0	CTV	1.5
Array cable replacement	2,920,000	0.003	48	3,000,000	CLV	1.5

5.11 End-of-life phase definitions

The end-of-life (EoL) phase encompasses the full set of activities associated with the retirement of the wind farm, from the physical removal of all offshore assets through to the final disposal or recovery of the structural materials. This phase therefore includes the decommissioning operations themselves as well as the subsequent processing of recovered components. Once components are brought onshore, they are processed according to material-specific pathways that reflect current industrial practice and regulatory guidance for offshore wind decommissioning in European waters. Steel and copper, which together represent the dominant mass fraction of a floating offshore wind turbine, are assumed to be largely directed to recycling given their well-established secondary markets and high residual value. Glass fibre and epoxy composite materials, primarily sourced from the turbine blades, present a more complex end-of-life challenge due to the limited availability of mature recycling routes at scale. Therefore, these fractions are split between incineration and landfill. Concrete, used in the platform and ballast structures is assumed to be fully landfilled. The following table summarises the main end-of-life treatment pathways assumed for each material, including recycling, incineration and landfill rates²².

Table 13: End-of-life treatment pathways

Material	Recycled (%)	Incinerated (%)	Landfilled (%)
Steel	92%	0%	8%
Copper	92%	0%	8%
Glass fibre	0%	50%	50%
Epoxy	0%	50%	50%
Aramid	0%	50%	50%
Concrete	0%	0%	100%

From an environmental standpoint, the EoL phase generates two opposing contributions to the lifecycle emissions balance. Disposal emissions arise from the landfill and incineration of non-recycled material fractions, charged using process-specific emission factors. Recycling credits are applied to represent the avoided primary production emissions associated with substituting virgin steel and copper with recovered secondary material, quantified against the primary-production emission factors for steel and copper.

From a financial standpoint, the phase produces scrap revenue from recovered metals and incurs disposal costs for landfilled and incinerated fractions. The assumed market prices and treatment costs used in the model are: steel scrap €0.25/kg; copper scrap €4.50/kg; landfill disposal €0.03/kg; and incineration €0.08/kg. It should be noted that inter-array and export cables are excluded from the EoL material accounting.

5.12 Environmental and social aspects

5.12.1 Environmental

The environmental KPIs prepared for incorporation into the enhanced LCoE model for the offshore wind case study are presented in Section 2.2.2 and operationalized in Section 4.1.

The table below summarizes the applicability of each of the environmental KPIs presented in Section 2.2.2 and Section 4.1 for the case study.

Table 14: Environmental KPIs included in the LCoE_e model

Environmental KPI	Reference value	Unit	CAPEX _{env}	OPEX _{env}	DECEX _{env}	LCoE _e	Reference to value	Additional comments
Climate								
KPI E1 – Avoided GHG Emissions	170.20	€/tCO ₂ eq	X	X	-	-	Social Cost of Carbon	See Table 15 in Section 5.12.2. Includes GHG damage and avoided grid emissions
KPI E2 – Additional carbon uptake							Data not available on carbon uptake	
KPI E3 – Release of sequestered carbon							Data not available on release of sequestered carbon	
KPI E4 – (Reduced) GHG-emissions from fossil-based activities	1	€/MW h	-	-	X	-	Section 5.11	Avoided primary production emissions associated with substituting virgin steel and copper with recovered secondary material
Water quality								
KPI E5 – Increased nutrient load							Data not available on nutrient load	
KPI E6 – Removal of nutrients							Data not available on nutrient removals	
KPI E7 – Release of chemicals and other pollutants							Data not available on release of chemicals	
KPI E8 – Uptake and possible removal of chemicals							Data not available on removal of chemicals	
Fauna and flora								
KPI E9 – Protection of benthic vegetation							Data not available on benthic vegetation	
KPI E10 – Protection of benthic fauna							Data not available on benthic fauna	
KPI E11 – Increased (or decreased) diversity in flora and fauna							Data not available on diversity in flora and fauna	
KPI E12 – More (or less) rare and protected species							Data not available on protected species	
KPI E13 – Changes in commercial species							Data not available on changes to commercial species	

KPI E14 – More (or less) invasive species					Data not available on invasive species
Other environmental KPIs					
KPI E15 – (Adverse) Visual impacts of the offshore installations	0	€			As distance to shore is 50 km and thus more than 30-40 km no adverse visual impact is expected
KPI E16 – Noise pollution during construction, operation and decommissioning					Data not available on noise levels during construction, operation and decommissioning. However, the EIA is expected to advice on mitigative efforts to suppress noise levels
KPI E17 – Changes in air quality during construction and decommissioning					Data not available on changes in air quality. Likely addressed in an EIA
KPI E18 – Reduction of the human use value					Data not available on the current use of the area

As seen from the table it is mainly the environmental KPIs related to ‘Climate’ and GHG-impacts that are included in the enhanced LCoE-model for the case study. The KPIs related to ‘Water quality’ are omitted from this model due to lack of data specific to the case study. The same goes for the KPIs related to ‘Fauna and flora’ for which data is not available. However, it must be noted that the effect of including KPI E9-14 is likely minimal, as presented in Section 4.1.1 on ‘Biodiversity and abundance effects’.

From the group ‘Other environmental KPIs’ only KPI E15 is included using a value of zero to reflect the fact that at a distance of 50 km from shore, no adverse visual impact from the offshore wind farm is expected as the threshold commonly referred to is a distance of 30-40 km.

5.12.2 Social

This section presents the input values assigned to the KPIs incorporated into the enhanced LCoE model for the offshore wind case study in Scotland. These are intended to capture broader societal impacts across the project lifecycle, alongside conventional techno-economic parameters.

The selected KPIs are defined in Section 2.2.3 and further developed in Section 4.2.

Data and monetary values were obtained from a combination of literature review of EU tendering processes (particularly the French AO8 tender scheme), Scottish case studies and French policy frameworks, and other UK and global publications.

The table below presents how each social KPI has been translated into an economic value of reference for its application on the enhanced LCoE model. The selected monetary values mainly reflect social mitigation measures, community funds, coexistence payments, stakeholder engagement activities, employment-related initiatives, and inclusivity programmes. These values are generally expressed in €/MW, €/MW-year, or annualised project costs to facilitate integration into CAPEX, OPEX, or enhanced LCoE calculations.

KPIs under the *Social Acceptance and Licence to Operate* category—namely S1 (Place Attachment), S2 (Cultural Landscapes), and S4 (Technology Acceptance – NIDs)—are highly context-dependent and influenced by site-specific characteristics. Their assessment is shaped by local socio-cultural conditions, stakeholder perceptions, and prior experiences, which introduces a degree of subjectivity and potential bias.

Some KPIs within the *Regional Economic Development* category are not fully internalised within the enhanced LCoE framework, as they do not directly affect project cash flows. KPI S11 (Employment) primarily contributes to broader economic outcomes, such as GDP generation, rather than to the financial performance of the project itself. Furthermore, its impact in terms of job quality is highly dependent on the opportunity cost of labour and reference scenarios, which vary according to regional and demographic conditions.

Similarly, KPI S12 (Local Small and Medium Enterprise (SME) Engagement) is understood to influence the distribution of project-related economic benefits rather than the overall level of costs. As such, it affects how financial flows are allocated within the local economy, without necessarily increasing or decreasing total project expenditures.

Overall, the table illustrates how contemporary offshore wind tender requirements and emerging social value practices can be translated into quantifiable inputs for an enhanced socio-economic offshore wind assessment framework.

Table 15: Social KPIs included in the LCoE_e model

Social KPI	Reference value	Unit	CAPEX _{soc}	OPEX _{soc}	DECEX _{soc}	LCoE _e	Reference to value	Additional comments
Social Acceptance and Licence to Operate								
KPI S3 – Environmental impact perception	10,000	€/MW	X	X	-	-	AO8 France	25% development 75% construction 15 m total max by year 1 of operation
KPI S5 – Community Benefit Schemes	686	€/MW-year	X	X	X	-	Neart na Gaoithe offshore wind farm (Scotland)	Up to 25 years lifecycle
KPI S6 – Community Ownership	6,667	€/MW-year	-	X	-	-	AO8 France	Operation only.
KPI S7 – Community Trust and Engagement	275,800; 203,508.8; 65,108.8	€/year	X	X	X	-	Estimate following AO8 France	Development (5 years): 275,800 €/year Construction (3 years): 275,800 €/year Operation (Years 1–5): 275,800 €/year Operation (Years 6–9): 203,508.8 €/year Operation (Years 10–25): 65,108.8 €/year Decommissioning (2 years): 65,108.8 €/year
Regional Economic Development								
KPI S8 – Labour Inclusivity (Vulnerable Groups)	5,332	€/MW	X	X	X	-	AO8 France	Total all phases
KPI S9 – Training and Employment of Apprentices	8,000	€/MW	X	X	X	-	AO8 France	Total all phases
KPI S10 – Co-location and Sea-Use Interactions	15,471	€/MW-year	X	-	-	-	French Law	Operation only Assuming 200,000 hours
Social Macroeconomics								
Social Cost of Carbon (SCC)	185	USD\$/ton CO ₂ -eq	-	-	-	X	Resource for the future, 2023	
Social Discount Rate (SDR)	3.5	% per year	-	-	-	X	UK SDR reference (2026)	3.5% per year for the first 30 years



As outlined in Section 4.2, the Social cost of carbon (SCC) is incorporated as a multiplier of carbon displacement, whereas the Social discount rate (SDR) substitutes the conventional discount rate (r). Assuming favourable carbon displacement and right alignment to minimum features requirements to SDR to be applicable, these adjustments are expected to improve the resulting values within the enhanced LCoE model. In addition, their straight inclusion in the equation suggests to have a significant impact on the overall results.

Additional socio-economic components (KPIs S3; S5 – S10) integrated into the project cost structure may increase overall expenditure relative to the traditional LCoE, which is typically insensitive to social dimensions. Nevertheless, these costs are aligned with emerging tendering practices and are largely unavoidable. Incorporating them into the enhanced LCoE framework enables a more comprehensive assessment, elevating social factors to the same analytical level as environmental and techno-economic performance.



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6 Results from case study and sensitivity analysis

The Enhanced LCoE (LCoE_e) extends the financial LCoE to incorporate environmental and social externalities. Environmental costs are monetised using the Social Cost of Carbon (SCC), and social costs are computed from six KPIs measured in €/MW or €/year. Both components use the Social Discount Rate (SDR = 3.5%) to reflect the longer time horizon of societal impacts.

In the following, the results for the conventional LCoE is first introduced, then the environmental and social aspects before the concluding LCoE_e is presented. Finally, results from a sensitivity analysis are provided.

6.1 Conventional financial LCoE component

The financial LCoE is computed by discounting all nominal costs and energy at 8% WACC over the full 32-year project lifetime. The result is 155.87 €/MWh, broken down as follows:

Table 16: Financial LCoE breakdown

LCoE Component	€/MWh	Share of Total LCoE
CAPEX (DEVEX + Manufacturing + Installation)	129.32	83%
OPEX (25-year O&M)	23.12	14.8%
DECEX (Decommissioning)	3.43	2.2%
Total Financial LCoE	155.87	100%

The high CAPEX share (83%) is typical for capital-intensive offshore infrastructure. The relatively modest DECEX contribution (2.2%) reflects discounting over a 32-year horizon.

The figure below shows the annual project cash flow (bars) and cumulative cash flow (line) from 2025 to 2056. Large negative outflows dominate the pre-operational period (manufacturing 2028–2029 and installation 2030–2031). Revenue from power sales (positive bars, 2032 onward) gradually offsets the accumulated deficit, with cumulative cash flow reaching zero in 2048 (payback year).

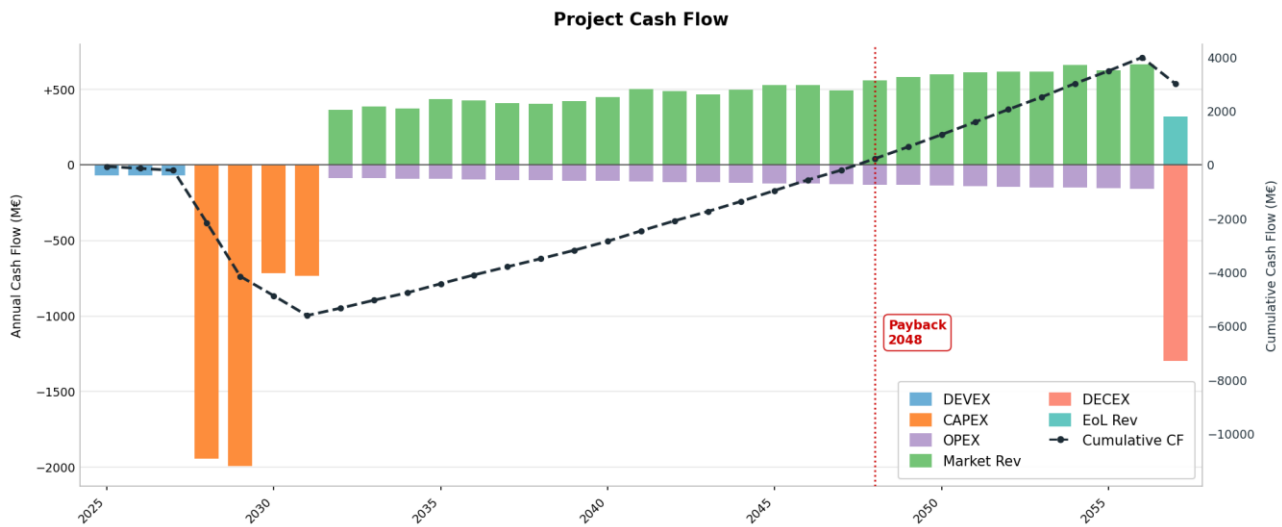


Figure 10: Annual and cumulative cash flow from 2025 to 2056

6.2 Environmental LCoE component

The environmental LCoE monetises net lifecycle GHG emissions using $SCC = 170.20 \text{ €/tCO}_2\text{eq}$ and discounts at $SDR = 3.5\%$. It decomposes into three sub-components, as follows:

Table 17: Results for the environmental LCoE component

Sub-component	Value (€/MWh)	Direction
GHG damage (gross emissions)	+8.33	Cost
EoL recycling credits	-1.00	Benefit
Avoided grid emissions	-17.02	Benefit
LCoE _{env}	-9.69	Net Benefit

The negative net environmental LCoE (-9.69 €/MWh) reflects the large societal benefit of decarbonising the electricity grid. Under SCC monetisation, each tonne of CO₂-eq avoided by generating from wind rather than grid-carbon sources is valued at €170.20, producing a net environmental benefit of 9.69 €/MWh that reduces the effective cost of the project.

6.3 Social LCoE component

Six social KPIs are monetised across project phases and discounted at $SDR = 3.5\%$ to compute the social LCoE component:

Table 18: Results for the social LCoE component

KPI	Description	LCoE _{soc} (€/MWh)	Share
KPI S3	Environmental impact perception	0.14	2.69%



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KPI S10	Colocation with other sea users	3.25	62.50%
KPI S6	Community ownership / benefit sharing	1.40	26.92%
KPI S5	Community benefits fund	0.22	4.23%
KPI S7	Community trust & engagement	0.06	1.15%
KPI S8	Labour inclusivity	0.05	0.96%
KPI S9	Training & employment	0.08	1.54%
Total LCoE _{soc}		5.20	100%

KPI S11 (colocation) dominates the social LCoE at 64.5% because it is assessed annually during the 25-year operational period at €15,500/MW/yr, a substantial ongoing cost reflecting the impact on other sea users (fishing, shipping, marine protected areas). KPI S15 (community ownership) contributes 27.8%, reflecting the relatively high unit cost of €6,700/MW/yr for benefit-sharing schemes in this reference scenario.

6.4 Total LCoE_e Summary

Table 19: Summary of values for enhanced LCoE

LCoE Component	Value (€/MWh)	Direction
Financial LCoE	155.87	Cost
CAPEX component	129.32	
OPEX component	23.12	
DECEX component	3.43	
Environmental LCoE	-9.69	Net Benefit
GHG damage	+8.33	
EoL recycling credits	-1.00	
Avoided grid emissions	-17.02	
Social LCoE	+5.20	Cost
KPI S3	+0.14	
KPI S5	+0.22	
KPI S6	+1.40	
KPI S7	+0.06	



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This report is currently under review by CINEA. Its contents are provisional and may be subject to change following the review process.

KPI S8	+0.05	
KPI S9	+0.08	
KPI S10	+3.25	
LCoE_e	151.36	Net Cost

The total LCoE_e of 151.36 €/MWh is 4.66 €/MWh lower than the financial LCoE (155.87 €/MWh). The environmental benefit of grid decarbonisation (−9.69 €/MWh) more than offsets the added social costs (+5.2 €/MWh), yielding a meaningful net reduction. This result is highly sensitive to the grid emission factor and the SCC, as shown in the sensitivity analysis.

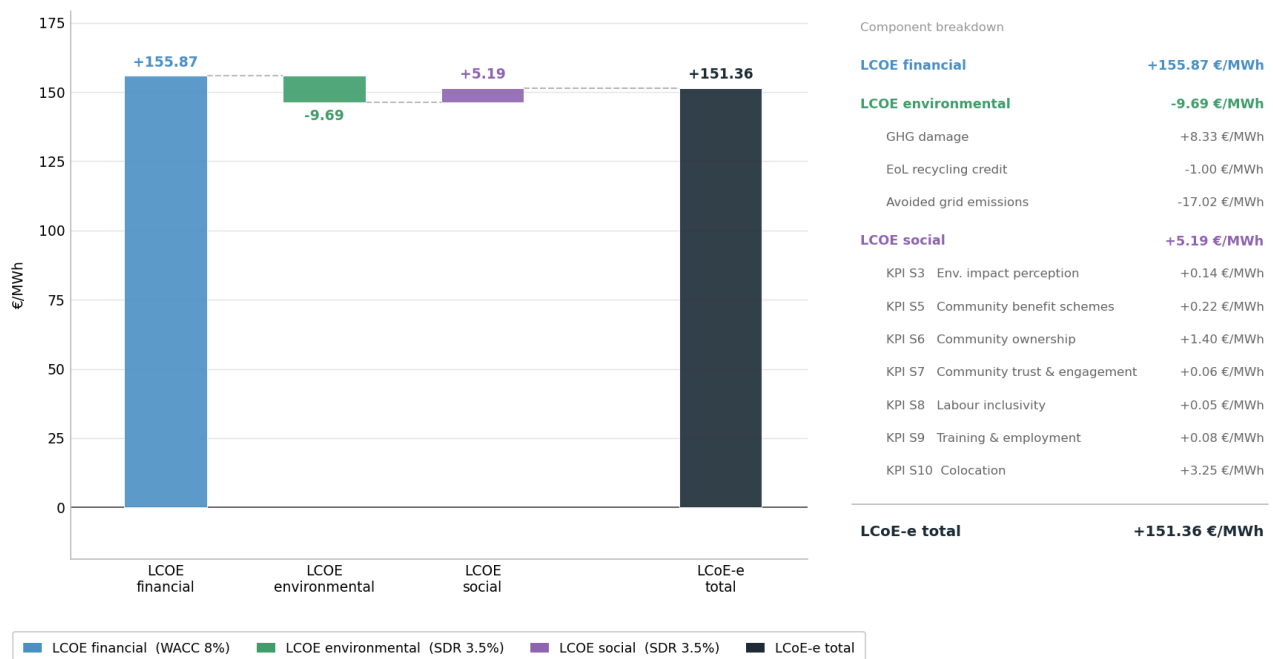


Figure 11: Overview of LCoE_e and contributions

6.5 Sensitivity Analysis

A one-at-a-time (OAT) sensitivity analysis is performed on the LCoE_e to identify the most influential parameters. Each parameter is varied independently over its uncertainty range while all other parameters are held at their baseline values.

Figure 12 shows the LCoE_e range for each parameter varied independently. The Social Discount Rate (SDR) emerges as the most influential parameter: a lower SDR (1%) increases the weight placed on long-term avoided emissions and social costs, while a higher SDR (7%) discounts these heavily, producing a LCoE_e range of approximately ±8–12 €/MWh relative to the baseline. The Grid Emission Factor is the second most influential driver, directly scaling the avoided-emissions benefit: a lower value (50 g CO₂-eq/kWh) reduces the LCoE_{env} credit and shifts LCoE_e upward, while a higher value (150 g CO₂-eq/kWh) amplifies it, yielding a range of approximately ±4–7 €/MWh.

The Financial Discount Rate (WACC) affects the present-value weighting of pre-operational costs against operational revenues; at 6% WACC the LCoE falls, while at 10% it rises, yielding a range of approximately ±15–20 €/MWh on the financial LCoE component. The Social Cost of Carbon scales all environmental cost components proportionally,

contributing a narrower range of approximately $\pm 1\text{--}2$ €/MWh on LCoE_{env} . Finally, halving or doubling all social KPI costs shifts LCoE_{soc} by approximately ± 2.5 €/MWh, with KPI S11 (colocation) dominating this sensitivity given its relatively large per-MW annual value.

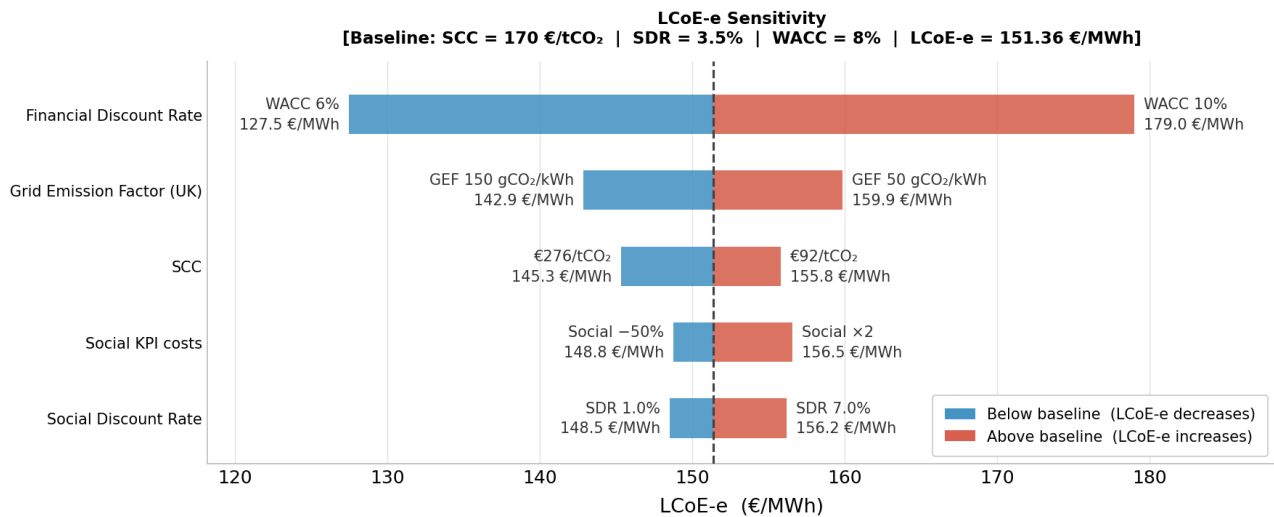


Figure 12: Results from sensitivity analysis

7 Conclusions and further work

This deliverable has presented the Enhanced Levelized Cost of Energy (LCoE_e) model developed within Task 7.3 of the INF⁴INiTY project. The model extends the traditional LCoE framework by incorporating socio-environmental externalities, providing a more complete and realistic basis for assessing the economic viability and broader societal value of floating offshore wind farm investments with nature inclusive designs.

The report has defined a comprehensive set of cost elements covering all major phases of a floating offshore wind farm's lifecycle — from development and manufacturing through installation, operation and maintenance, to decommissioning and end-of-life management. Alongside these cost elements, a structured set of key performance indicators has been established, spanning techno-economic, environmental, and social dimensions. The environmental KPIs address impacts ranging from greenhouse gas emissions and carbon sequestration to marine biodiversity, water quality, and human use values, while the social KPIs cover community acceptance, colocation with other sea users, employment, local economic development, and broader societal parameters such as the Social Cost of Carbon and the Social Discount Rate.

The INF⁴INiTY LCoE model integrates three main modelling components developed in close collaboration across the consortium: AEP estimation using DTU-W's minimalistic atmospheric boundary layer model; installation and decommissioning cost estimation using SINTEF's SeaSequence simulation tool for weather-constrained marine operations; and OPEX estimation using Mondragon University's probabilistic RAM model. The LCoE_e formula augments this financial baseline by adding environmental and social cost components, both discounted at the Social Discount Rate to reflect society's longer time horizon and preferences.

The model has been applied to a representative case study: a 1,005 MW floating offshore wind farm of 67 turbines sited in the Scottish Sea at 100 m water depth, consistent with the farm layout defined in INF⁴INiTY's deliverable 5.2. The baseline financial LCoE amounts to 155.87 €/MWh. When socio-environmental externalities are included, the environmental component contributes -9.69 €/MWh, a net benefit driven primarily by avoided grid emissions valued at the Social Cost of Carbon – while the social component adds +5.04 €/MWh, dominated by colocation compensation to other sea users and community benefit-sharing. The resulting total LCoE_e is 151.21 €/MWh. A one-at-a-time sensitivity analysis identifies the Social Discount Rate, the financial discount rate (WACC), and the grid emission factor as the most influential parameters, underscoring the importance of macro-economic and policy assumptions in floating offshore wind assessments.

The LCoE_e model presented in this deliverable forms a key input to the subsequent tasks of work package 7 in the INF⁴INiTY project. In Task 7.4, the model is integrated into the holistic techno-environmental optimisation framework developed by Mondragon University and PoliTO. The multi-level, multi-objective optimisation tool will enable site-reflective decision-making across the three INF⁴INiTY case study sites, considering technical performance inputs from WP1–WP6 alongside licensing requirements and project-specific constraints. The LCoE_e KPIs defined in this deliverable have been framed to ensure compatibility with this optimisation framework.

In Task 7.5, the wider lifecycle and impact assessment of the INF⁴INiTY innovations will build directly on the outputs of Tasks 7.3 and 7.4. This assessment will evaluate the energy, resource, carbon, macroeconomic, and socio-environmental impacts of floating offshore wind farms incorporating the INF⁴INiTY nature-inclusive designs, from cradle to grave. This will include a full Life Cycle Assessment of material and carbon flows, as well as national Input-Output modelling to capture macro-economic effects, and will be compared against business-as-usual reference scenarios for each of the three case study regions in the project: The Scottish, Adriatic and Baltic sea.



8 Appendix

Table 20: Overview of Techno-Economic KPIs

Group	Subgroup	Metric	Description	Unit
Technical KPIs	RAM KPIs (KPIs T1-T6)	T1 MTTF	The average time a non-repairable system or component operates before it fails. It is calculated by dividing the total operating time of all units by the number of failures.	[h]
		T2 MTBF	The average time between consecutive failures of a repairable system, including the time the system is repaired and returned to operation.	[h]
		T3 MTTR	The average time required to repair a failed system and restore it to full operation. It is calculated by dividing the total repair time by the number of repair events.	[h]
		T4 MTTW	The average time a system, user, or process waits before service or repair begins. It is calculated by dividing the total waiting time by the number of waiting events.	[h]
		T5 Access.	The ability to reach or use a site or system safely within operational limits and suitable weather conditions.	[%]
		T6 Time-based Availability	The proportion of time a system is operational and ready for use compared to the total planned time.	[%]
	Power- and energy related KPIs (KPIs T7-T11)	T7 Power density	The amount of power generated per unit area of a wind farm.	[W/m²]
		T8 Power quality	The stability and consistency of electricity, evaluated as the number of disturbances divided by the total observation time.	[%THD]
		T9 AEP	The total amount of energy a wind farm generates over a year.	[MWh]
		T10 CF	The ratio of actual energy produced by a system to the maximum possible energy it could produce over the same period.	[%]
		T11 Curtailment ratio	Curtailed energy divided by total potential energy.	[%]
Economic KPIs		T12 CAPEX	The total upfront cost of acquiring and installing a system or asset.	[€]



(KPIs T12-T20)	T13 OPEX	The ongoing costs of operating and maintaining a system over its lifetime.	[€]
	T14 DECEX	The cost of dismantling, removing, and disposing of a system at the end of its life.	[€]
	T15 LCC	The total cost of a system over its entire life, including CAPEX, OPEX, and DECEX.	[€]
	T16 LCoE	The average cost per unit of energy produced over a system's lifetime.	[€/MWh]
	T17 LVoE	The average value or revenue earned per unit of energy generated over a system's lifetime.	[€/MWh]
	T18 IRR	The discount rate at which the net present value of a project's cash flows equals zero.	[%]
	T19 NPV	The total value of future cash flows from a project discounted to present terms minus initial investment.	[€]
	T20 ROI	The ratio of net profit from an investment to its total cost, expressed as a percentage.	[%]

Table 21: Overview of Environmental KPIs

Group	KPI Name	Description	Unit / Type
Climate	E1 Avoided GHG emissions	Reduction of greenhouse gas emissions due to renewable energy replacing fossil fuels	[tCO ₂ -eq/year]
	E2 Additional carbon uptake	Increased carbon sequestration from enhanced marine ecosystems	[tCO ₂ -eq/year]
	E3 Release of sequestered carbon	Carbon released due to seabed disturbance or ecosystem degradation	[tCO ₂ -eq/year]
	E4 Lifecycle GHG emissions	Emissions from manufacturing, installation, operation, and decommissioning	[tCO ₂ -eq/year]
Water quality	E5 Increased nutrient load	Release of nutrients (e.g. nitrogen, phosphorus) into marine environment	Qualitative / [kg/year]
	E6 Nutrient removal	Reduction of nutrients via ecosystem activity (e.g. shellfish, algae)	[kg/year]



	E7 Release of pollutants	Emission of chemicals or pollutants during project lifecycle	Qualitative / concentration
	E8 Pollutant removal	Uptake/removal of pollutants through biological processes	Qualitative
Fauna and flora	E9 Protection of benthic vegetation	Preservation of seabed flora (e.g. seagrass, algae)	Qualitative
	E10 Protection of benthic fauna	Preservation of seabed fauna (e.g. filter feeders)	Qualitative
	E11 Biodiversity change	Change in species diversity (increase or decrease)	Qualitative / index
	E12 Rare/protected species impact	Change in abundance of protected species	Qualitative
	E13 Commercial species impact	Effect on commercially important species (e.g. fish stocks)	Qualitative / biomass
	E14 Invasive species impact	Change in presence or spread of invasive species	Qualitative
Other environmental KPIs	E15 Visual impacts	Visual impacts of the offshore installations affecting human wellbeing i.e. people.	[€/year] / [€]
	E16 Noise pollution	Noise pollution affecting people and fauna	Qualitative
	E17 Air quality	Changes in air quality affecting people and nature	Qualitative / concentration
	E18 Use values	Restriction of access to commercial and recreational activities	Qualitative / [€]

Table 22: Overview of Social KPIs

Group	KPI Name	Description	Unit / Type
Social acceptance and license to operate	S1 Place attachment	Impact on emotional, cognitive and behavioural bonds to the place	Qualitative
	S2 Cultural landscapes	Impact on cultural heritage and landscape value	Qualitative
	S3 Environmental impact perception	Stakeholder perception of environmental effects	Qualitative

	S4 Technology acceptance (NIDs)	Acceptance of Nature Inclusive Designs	Qualitative
	S5 Community benefits	Financial contributions to local communities	[€/MW/year]
	S6 Community ownership	Degree of local ownership or financial participation	[%]
	S7 Community trust & engagement	Level of stakeholder engagement and trust	Qualitative
Regional economic development	S8 Labour inclusivity	Inclusion of vulnerable groups in workforce	[Hours] / [%]
	S9 Apprenticeships & training	Investment in workforce development	[Hours] / [# of apprentices]
	S10 Co-location & sea-use interaction	Impact on interaction with other sea-users.	[€/MW/year]
	S11 Employment	Jobs created (direct and indirect)	[Jobs/MW]
	S12 SME engagement	Participation of small and medium enterprises	[%] / Qualitative
Social macroeconomics	Social cost of carbon	Economic cost of emissions	[€/tCO ₂]
	Social discount rate	Discount rate reflecting societal preferences	[%]

