CL-Windcon

Closed Loop Wind Farm Control

# DELIVERABLE REPORT

# D4.6. Cost-benefits analysis

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# LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| ADP | Abiotic resource depletion |
| AEP | Annual energy production |
| AP | Acidification potential |
| BOP | Balance of Plant |
| CAPEX | Capital Expenditure |
| CED | Cumulative energy demand |
| CLR | Closed loop recycling |
| CTV | Crew transfer vessel |
| DEL | Damage Equivalent Load |
| DEVEX | Development Expenditure |
| EoL | End of life |
| EP | Eutrophication potential |
| EPD | Environmental product declaration |
| FAETP | Freshwater aquatic ecotoxicity potential |
| GWP | Global warming potential |
| GW | Gigawatts |
| HTP | Human toxicity potential |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| JUV | Jack-up vessel |
| KPI | Key performance indicator |
| LCA | Life cycle assessment |
| LCC | Life Cycle Costing |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LCOE | Levelized Cost of Electricity |
| MAETP | Marine aquatic ecotoxicity potential |
| MP | Raw materials |
| MW | Megawatt |
| O&M | Operation and maintenance |
| ODP | Ozone layer depletion |
| OLR | Open loop recycling |

| | |
|---|---|
| OPEX | Operational Expenditure |
| PED | Primary energy demand |
| POCP | Photochemical ozone creation potential |
| ROV | Remotely operated vehicle |
| RWF | Reference Wind Farm |
| RUL | Remaining Useful life |
| TETP | Terrestrial ecotoxicity potential |
| WACC | Weighted average cost of capital |

# 1 EXECUTIVE SUMMARY

Deliverable D4.6 is the main result of task 4.5 called "Feasibility versus Economics & Environment of advanced integrated control", which can be broken down into two fundamental blocks; the economic block or Life Cycle Costing (LCC) and the environmental block or Life Cycle Analysis (LCCA).

The Project has developed advanced control algorithms for axial induction and wake redirection to optimize the operation of a wind farm, making a balance between annual energy production, lifetime and O&M cost, aimed at minimizing the LCoE. To that end, it has applied techniques as loads-optimized power curtailment, event triggered Individual Pitch Control (IPC) for loads reduction under partial wake conditions, fault-tolerant and fast wake recovery techniques.

WP2 was addressed to develop specific algorithms to cover the following aspects:

- Develop wind farm control algorithms for the induction-based control technology
- Develop wind farm control algorithms for wake redirection control
- Develop wind farm control algorithms for power curtailment
- Design supporting wind farm control technologies for improved load mitigation.
- Develop control algorithms to reduce the impact of sensor failure on wind farm performance and availability.

Among them, deliverable D4.1 in task 4.1 calculates the component fatigue loads for multiple yaw misalignment, wind speed and turbulence intensity combinations. An input was needed regarding look up tables DEL (damage equivalent load) /ADC (actuator duty cycle) for a given yaw angle, wind speed and turbulence intensity. This was necessary to support the sensitivity analysis of the failure rate estimation, as well as for the Lifetime Extension assessment. An input also needed from IK4-IKERLAN dealing with an industry insight on the probable failure rate distribution across the selected wind farm.

With this information, deliverable D4.5 leaded by Ramboll, evaluated the economic feasibility of wind farm control technologies. For the study the wake steering control concept has been chosen to compare maintenance scenarios without and with such a controller installed, as recent results indicated that this is the most promising technology. In order to quantify the impact of the controller on the wind farm availability and the OPEX, an O&M tool was developed, and simulations run which were the base for the LCC and LCA analysis.

Thus, this deliverable analyses the impact of incorporating the new integrated control system into an offshore wind farm that serves as a model or reference. For this, the reference Norcowe Windfarm, located in the North Sea has been selected. With a nominal capacity of 800 MW, it incorporates 80 turbines of 10 MW each. The farm is located 80 km from land and has two offshore marine substations and an onshore substation. The foundations have been considered to be jacket type although the refence wind farm was defined with monopiles. The study has analysed the economic and environmental impact of the new technology through a detailed analysis of the complete life cycle of the windfarm throughout its 25 years of useful life and 1 additional year for dismantling. The reference scenario has been called "Base" or "Baseline" and the one with the new control system has been called "Yaw".

The main result of the wake control technology is the increase in the structural load experienced by the downstream wind turbines, but also the reception of a higher quality wind (with less turbulence). This determines that failure rates are modified by these effects and consequently the operation and maintenance activities. On the other hand, the greater load also allows to increase the electrical production (AEP) significantly, improving the LCoE in a few tenths.

The results obtained have been less relevant than expected, although a small environmental and economic improvement compared to the base case has been achieved. Specifically;

From the economic standpoint and considering the costs at present value, the increase in the O&M operations suppose around additional € 3.59 million (for 25 years), which is really a small number with extra incomes for the AEP rounding € 30.47 million. Therefore, the gaining during the whole lifetime rounds € 26.88 million that represents the 1.10% of the whole project costs.

| MAIN CONCLUSIONS (YAW/BASE) | Unit | Absolute | Relative |
|---|---|---|---|
| Increase in LCC (Present Value) | € | -3,592,100 | -0.15% |
| Increase in Net Energy sales (Present Value) | € | 30,479,236 | 0.79% |
| Net differences | € | 26,887,136 | 1.10% |

**Table 1. Main economic conclusions (savings)**

Consequently, the LCOE has been slightly improved from **31.55 €/MWh to 31.35 €/MWh,** representing a gaining of 0.63 %, if we consider an average price of the electricity of **50 €/ MWh**. With this scenario. The final economic results are summarized in the next table.

| SCENARIOS/Concepts | Units | Base Fix | Base YAW |
|---|---|---|---|
| Total Present Value Costs | € | 2,448,294,807 | 2,451,886,907 |
| Total Energy Produced (Non discounted) | MWh | 113,556,000 | 114,448,000 |
| Total Energy Produced (Present Value) | MWh | 77,603,141 | 78,212,726 |
| Total incomes sales of energy (50€/MWh) | € | 3,880,157,065 | 3,910,636,301 |
| Average Cost (Present Value) per MW | €/MW | 3,060,369 | 3,064,859 |
| Total Net Energy Production (NPV) | MWh/MW | 97,004 | 97,766 |
| **LCOE** | €/MWh | 31.55 | 31.35 |
| *Years* | *Nº* | *25+1* | *25+1* |
| *WACC nominal* | *%* | *5.19%* | *5.19%* |
| *Inflation Rate* | *%* | *1.5%* | *1.5%* |

**Table 2. Main project economic results.**

From the environmental point of view and using a Gabi environmental software, nine categories of impact has been measured for both options, comprising abiotic depletion, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, photochemical oxidant creation potential and terrestrial ecotoxicity potential. The results show that "Yaw control" contributes with a negligible impact within each of these impact types (less than 1%) when normalized per kWh of electricity production, in comparison to the "Base" case. In two categories (Eutrophication potential and acidification potential), the results for the "Yaw" scenario were even worst that the “Base” scenario. The environmental results are affected by the slight increase of the O&M operations requiring additional spare parts, vessels, mobilizations, crew, etc. The final environmental results are included in the table below.

| LCA, Impact categories | Baseline | Yaw control |
|---|---|---|
| Abiotic Depletion (mg Sb-eq/kWh) | 0.072291 | 0.071731 |
| Acidification Potential (g $SO_2$-eq/kWh) | 0.01747 | 0.017476 |
| Eutrophication Potential (g $PO_4$-eq/kWh) | 0.00162 | 0.001623 |
| Freshwater Aquatic Ecotoxicity Pot. (g DCB-eq/kWh) | 0.009524 | 0.00947 |
| Global Warming Potential (g $CO_2$-eq/kWh) | 5.184185 | 5.148826 |
| Human Toxicity Potential (g DCB-eq/kWh) | 0.972541 | 0.965257 |
| Marine Aquatic Ecotoxicity Pot. (g DCB-eq/kWh) | 437.476 | 434.153 |
| Photochemical. Oxidation Creation Pot. (g Ethylene-eq/kWh) | 0.00194 | 0.001933 |
| Terrestrial Ecotoxicity Potential (g DCB-eq/kWh) | 0.008354 | 0.00829 |

**Table 3. Main project environmental results**

We must indicate that calculations for the modified failure rates are quite complex and the impact in the O&M operations as well, as the evolution overtime of a turbine submitted to additional loads but also to “clean” wind are not easy to infer. The project therefore intends to be a theoretical exercise of the potential evolution of the turbines components’ behaviour supported by some experimental data received from the Sedini Windfarm and the wind tunnel experiments, but results cannot be considered definitive but a guiding result requiring additional research.

Some sensibility analysis will be included in deliverable D5.2 “Business models”, to determine how economic and environmental values could be modified in case some parameters vary.

This deliverable also investigates the life extension of the constitutive components of a wind turbine affected by the changing loads in the yaw scenario. The main conclusion is that the more affected element is the hub. The differences occur for the Mx and My moments and are caused by the rotor plane which is turned out of the wind direction for the yaw case. The wind conditions in which the yaw controller is activated have an occurrence probability of approximately 33% of the lifetime. This is significantly high and has an impact on the loads in the controller case. The rotor plane experiences a cross wind component for which in one half of the rotor plane the blade needs to go against that wind and for the other half it goes with the wind. This alternating loading and unloading are transferred to the hub and presents additional load cycles which are reflected in the results of the rotating coordinate system. The turbulences in the wind also have a stronger effect on the loads when the turbines are inclined than when the yaw error is 0°.

# 2 INTRODUCTION

CL-WINDCON has developed advanced control algorithms for axial induction and wake redirection that optimize the operation of the wind farm for a balance between annual energy production, life, and O&M cost, aimed at minimizing lifetime LCoE. The Life Cycle Costing and the Life Cycle Assessment measure how this algorithms impact in costs and environmental emissions during the whole windfarm lifetime.

Therefore, this deliverable D4.6, is organized in two separate sections; the first one is a Life Cycle Costing (LCC) whilst the second is a Life Cycle Assessment (LCA) , which compare two scenarios called "baseline scenario" where the turbines in a wind farm follow one single strategy and the "yaw scenario" where each turbine acts independently according to the wakes its receive and some other strategies and tries to optimize the overall energy output. The deliverable intends to clarify if the new Wind Farm control technology might be profitable from an economic viewpoint and sustainable from an environmental standpoint.

Both reports make up the final reporting for the electricity produced from 800 MW offshore wind power plant of DTU 10 MW RWT according to the requirements of the International Organization for Standardization (ISO) 14040 and 14044 for LCA.

The Life Cycle Costing (LCC) is quite a new tool and is not as standardized as the LCA. There are some tools available for different market niches but still undeveloped in many others. Life cycle costing (LCC) is defined in the ISO standard, Buildings and Constructed Assets, Service-life Planning, Part 5: Life-cycle Costing (ISO 15686-5) as an "economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability." Life-cycle costing (LCC) means considering all the costs that will be incurred during the lifetime of the product, work or service.

The LCC has been implemented with the same boundary conditions as the LCA. The results are shown in Excel to allow an easy checking of formulation. Some of the cost data were collected from primary sources; mainly very recent reports on wind farm costs as Norcowe reference wind farm[1], BVGA LCC report[2], Statistics from WindEurope 2019[3], Fraunhofer reports[4], IRENA[5], World leading experts in Offshore wind[6], NREL[7],[8] and some others were adaptation made by the author.

Finally, results in the O&M section were directly a transference from D45[9] entitled "O&M Cost Modelling" prepared by the working team. Data were accepted as they are, and any interpretation must be addressed to the authors. The O&M section is where the differences in the Wind Farm behavior due to the new control strategy is showed and thus, key to understand if the technology will be sustainable and affordable.

# 3 DESCRIPTION OF THE EXERCISE. REFERENCE DATA

This chapter give a summary of the boundary conditions of the reference wind farm and wind turbine, all defined in CL-Windcon deliverable D1.1 (Definition of reference scenario and simulations) and described in deliverable D45 (O&M Cost Modelling) as well.

## 3.1 Reference wind farm

For the simulation, a reference wind farm (RWF) site called NORCOWE (CL-Windcon Deliverable 1.1, 2017) was chosen. The RWF has been developed in a Norwegian project called NORCOWE by industry and science partners. The RWF is located around 80 km west of the German island Sylt, and near by the met mast FINO 3 is installed (NORCOWE, 2019). The real RWF comprises 80 turbines of the type DTU 10 MW RWT and the layout of the wind farm can be seen in next figure. Position 26 and 61 in the layout are the positions of substations. The distance between the rows is 8 rotor diameters and the distance between the turbines is 7 rotor diameters. The RFC differs from the real one in the selected foundation for the simulation. We used jacket type instead of the real one (monopiles).

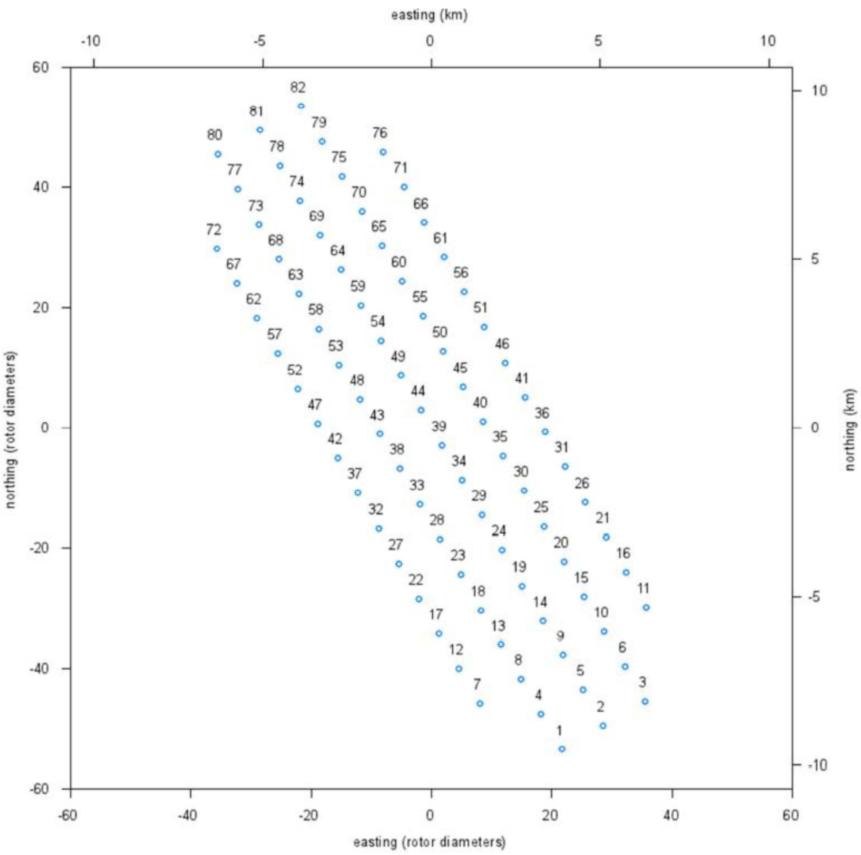


**Figure 1. Layout of the NORCOWE wind farm with eighty 10MW turbines**

## 3.2 Environmental Conditions

For the simulation, historical weather data of FINO 3 has been utilized. FINO3 is one of three research platforms supported by the German government allocated in North and Baltic Sea close to permitted offshore wind farms and is collecting among others weather data (FINO3, 2019). The wind rose of FINO3 can be seen in Figure 7 of CL-Windcon deliverable 4.5 (O&M Cost Modelling).

## 3.3 Reference Wind Turbine

For the simulations the 10MW DTU reference wind turbine, presented in (CL-Windcon Deliverable 1.1, 2017) and defined in (Bak, et al., 2013), has been used. The main characteristics are listed in next table.

| Description | Value |
|---|---|
| · Rated Power (MW) | 10 |
| · Rotor Diameter (m) | 178.3 |
| · Hub height (m) | 119 |
| · Cut-in speed (m/s) | 4 |
| · Rated Speed (m/s) | 11.4 |
| · Cut-out speed (m/s) | 25 |
| · Cut-in Rotor speed (RPM) | 6 |
| · Cut-out Rotor speed (RPM) | 9.6 |

**Table 4. DTU 10 MW Reference Wind Turbine Main Characteristics (Bak, et al., 2013)**

The wind turbine is mounted on a jacket structure of which the main parameters can be found in next table.

| Description | Value |
|---|---|
| · Number of legs (units) | 4 |
| · Base Width (m) | 33 |
| · Top Width (m) | 16 |
| · Interface elevation (mMSL) | 26 |
| · Transition Piece height (m) | 8 |
| · Jacket legs outer diameter (upper/lower leg mm) | 1422/1828 |
| · 1$^{st}$ eigen frequency (1$^{st}$ bending mode) (Hz) | 0.2635 |

**Table 5. Jacket Substructure Main design parameters (Innwind Deliverable D4.34 , 2012)**

To feed the yield model, the power curve of the DTU 10 MW from the Innwind project (Innwind Deliverable D1.21, 2012) was used and is shown in next figure. It is characterized by a cut-in wind speed of 4 m/s, a rated wind speed of 11.4 m/s, and a cut-out wind speed of 25 m/s.

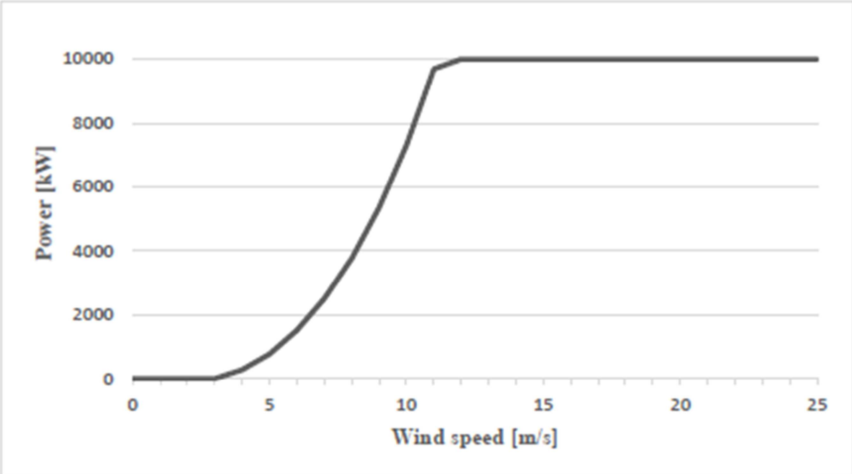


**Figure 2. DTU 10 MW Reference Wind Turbine Power Curve. Plotted with data from (Innwind Deliverable D1.21, 2012)**

## 3.4 Breakdown of turbine components.

The LCC and the LCA require to disaggregate the turbine into its different components and analyse the costs and the environmental impact over the entire life cycle of the constituent elements. The components used in this study are seven: gearbox, generator, pitch system, yaw system, blades, main shaft, and electrical system. This structure allows analysing changes in reliability due to applied controller technologies which are driven by the yaw and pitch system modifying the failure rates as described in Figure 3

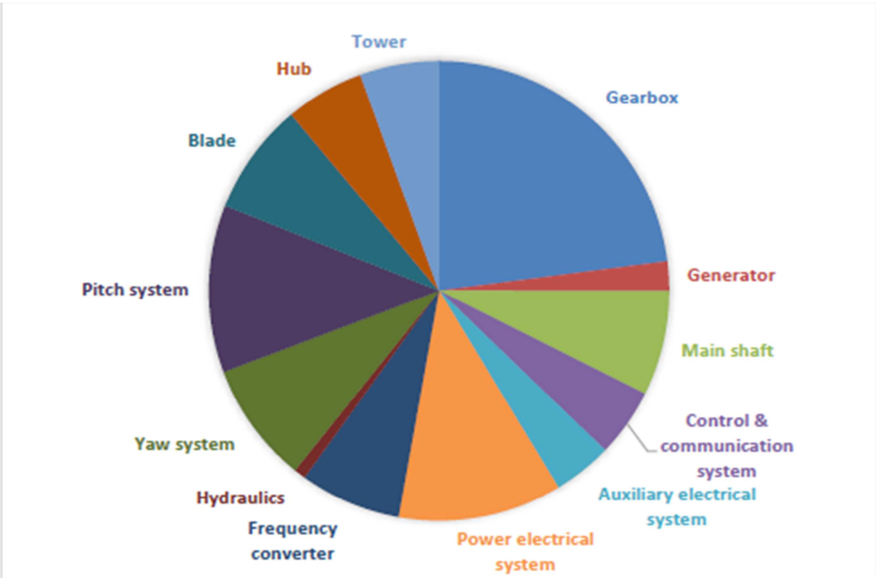


**Figure 3. Normalised annual failure rates of the DTU 10 MW RWT, (Hendriks, 2015).**

## 3.5 Comparison “Baseline” against “Yaw control” scenarios

The purpose of the present studies relies in the comparison of the “Baseline” and the “Yaw control” scenarios. The impact of the wake steering control strategy on fatigue load distribution is the cornerstone of the study. Turbine level load data from wake steering control simulations is used to estimate damage equivalent loads (DEL) for the complete range of wind conditions and their corresponding yaw misalignments. This data is combined with farm-level wind speed and direction distributions and thereby the fatigue loading all along the wind farm has been estimated. Please refer to deliverable D45 (O&M Cost Modelling) for additional information.

The impact of the yaw control strategy will be in the operational phase, specifically in the operation and maintenance of the windfarm and in the energy production.

Generally speaking, in a wind farm, the wake in front of a wind turbine depends on the wind direction and wind velocity. A turbine can experience no wake (free stream), partial wake (the wake hitting only part of the rotor) or full wake. All these wake situations have different impact on the loading. Partial wake inflow conditions, for instance, lead to higher blade loading than full wake conditions.

The working team in deliverable D4.5 has considered a simplified simulation setup where the wakes have been approximated by a free-stream wind field with higher turbulence and a lower (uniform) wind speed. When the wakes are redirected aside from downstream turbines, the wake effects at second line of turbines will be weaker and thus, the larger portion of free stream inflow will result in lower turbulence and higher wind velocity, what modifies the failure rates and the corresponding O&M costs but also increasing the energy output of the whole wind farm.

However, a deeper analysis with a more realistic wake model, with a huge amount of simulations to model the loads properly for each turbine in the farm, each wind direction and each wind velocity, could provide different results, as recently shown in the literature[10]. There, the authors report lifetime fatigue load reductions under wake steering.

In this study, however, we have considered the results of deliverable D4.5 working team, which main results are an increase in the O&M cost and environmental emissions when yawing the wakes and an increase in the wind farm energy output. To cover the second option, deliverable D5.2 introduces a scenario where the O&M costs and emissions are kept constant in both scenarios whilst the energy output is increased.

Hereinafter, chapter four revises the Life Cycle Costing, whilst chapter five investigates the Life Cycle Assessment

# 4 LIFE CYCLE COSTING

## 4.1 Methodology

The methodology to draw up this section was based on the usage of scientific papers, annual reports from large sectorial consultancy companies and internal data generated within the project. The main purpose of the section is to conduct a qualitative and quantitative analysis to determine whether, the "yaw control solution" is economically feasible to penetrate the wind market sector.

Supported by former intermediate reports (specially D45, O&M Cost Modelling) an LCC and the LCOE are calculated in two different scenarios; offshore bottom-fixed wind farm with non-controlled strategy, and the same with a yaw-controlled strategy for the whole wind farm. The report finalises with some conclusions or recommendations to path the way for the market uptake.

The qualitative analysis was carried out through the consultation of numerous and updated annual reports of international organizations such as the Global Wind Energy Council (GWEC), International Renewable Energy Agency (IRENA), International Energy Agency (IEA), WindEurope or BVGA. These reports described the current situation of the wind energy market and the possible future trends, giving a general overview of the potential growth of the market and providing some cost estimations.

The economic-quantitative analysis, instead, concerns the calculation of the Life Cycle Costing (LCC) and the Levelized Cost of Energy (LCOE) of the two strategies. The economic evaluation was supported by scientific and public literature, such us Guide to an offshore wind farm, BVGA and Catapult, 2019[2], Forecasting Wind Energy Costs and Cost drivers, the view of the world leading experts NREL, 2016[7], Cost of Wind Energy Review, NREL[8], 2015, Carbon Trust, 2015[22], Parametric CAPEX, OPEX, and LCOE, Cranfield University, 2018[23], among others.

Some internal data arising from the pilot experience and Qi Energy calculations were also used to elaborate the final tables. An excel spreadsheet was elaborated to support all the calculations in open source to be managed by the CL Windcon partners' technical staff.

The final recommendations are an opinion of the Qi Energy authors according to the findings encountered and the calculations done.

## 4.2 Life Cycle Costing definition.

The LCC considers all the costs that are generated by the construction, operation and maintenance and dismantling of the referenced wind farm with non-controlled strategy (hereafter "Baseline" **or "Reference")** and the same wind farm when applied the yaw-controlled strategy (hereafter **"Yaw").**

**Life Cycle Costing** = *Agency costs (R&D costs + Capital costs + projected life-time operating costs + projected life-time maintenance costs + projected renewal costs + projected disposal costs (asset disposal-residual value) + User Costs.*

User costs are usually described as the cost effects (extra costs) in a user of an infrastructure during the whole life in case they exist. For instance, if you modify a highway adding a new lane, the drivers are affected during the construction, losing time that must be also quantified. In our case, we will consider ***user cost as negligible*** as the marine traffic will not be specially affected by the works and in case they will, the impact could be considered equivalent for the two scenarios, so the consensus is to consider ***user costs as zero***.

Life-cycle costing (LCC) means considering all the costs that will be incurred during the lifetime of the product, work or service.

- Purchase price and all associated costs (delivery, installation, insurance, etc.)
- Operating costs, including energy, fuel and water use, spares, and maintenance
- End-of-life costs (such as decommissioning or disposal) or residual value (i.e. revenue from sale of product)

Article 68(2) of Directive 2014/24/EU and Article 83(2) of Directive 2014/25/EU provides details on how LCC approaches can be used as part of public procurement procedures.

LCC may also include the cost of externalities (such as greenhouse gas emissions) under specific conditions, but we will not include them in the calculations to avoid misunderstanding of real costs. However, from the LCA and LCC, we can infer the double vision; environmental and costs.

In the exercise, we will compare the following:

1. Scenario 1. Offshore Wind farm with a total nominal capacity of 800 MW, with 80, 10MW turbines with bottom-fixed foundation (jacket system) and greedy control strategy (baseline).
2. Scenario 2. Offshore Wind farm with a total nominal capacity of 800 MW, with 80, 10MW turbines with bottom-fixed foundation (jacket system) and yaw-controlled strategy (yaw).

In the boundary conditions bullet, a detailed description of the working conditions is included.

## 4.3 Time to market and other considerations

The moment in which the technology can be introduced in the market is important because it affects the costs that evolve till that specific date. The competing technologies that evolve in parallel might put the market uptake at risk (for instance tidal technologies or alternative clean energy generation).

The analysis has considered that project construction starts (FID, Final Investment Decision) in 2022 (figures are taken from trends to that specific moment).

In this study, we have assumed than DEVEX (Development expenditure for the preliminary studies, that usually takes 3 years) and CAPEX (Capital Expenditure after the FID) that also takes 3 years for a huge Wind farm), occur in year “0”, where all the investment and preliminary analysis is done. This deviation, that can modify the final LCOE (due to the WACC effect), is applied to the two scenarios, so the effect is offset and do not impact in the final LCOE differences.

We do not consider the reuse, recycling or disposal at the end of life, as these figures could introduce a distortion in the results disguising the impacts of the different technologies. We have not included financial expenses or a contingency cost of 5% as some authors recommend.

For the calculation of the O&M costs (the key cost component that introduces the main variation among the two scenarios), we followed, as commented, the results provided in D4.5 by the corresponding working team lead by Ramboll.

The WACC may be defined in post-tax terms. Owing to highly variable tax rules as well as the use of the tax code to incentivize wind energy in some countries, this survey has considered an average 25% taxes. Under these conditions, respective equity returns should reflect the annual average rate of return for equity positions after expenses and taxes. We have assumed an **inflation rate of 1.5%** (last announcements recommend reducing it from the conventional 2% as inflation rates in developed countries seems to suffer from stagnation**)**, financing **of 30% own resources** and **70% debt** and a **nominal WACC of 5.19% (from D4.5).**

## 4.4 Boundary conditions

The system boundary conditions include:

- Design and development
- Construction and commissioning
- Operation
- Maintenance
- Dismantling (decommissioning)

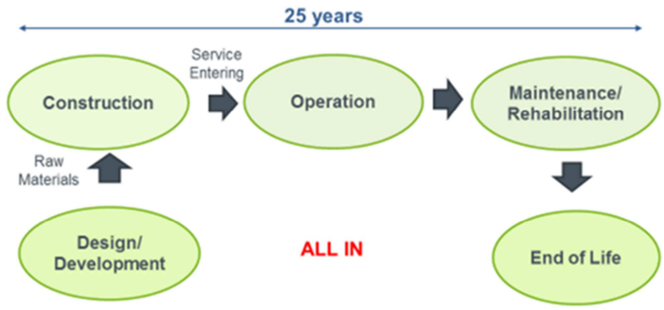


**Figure 4. Boundary conditions for the LCCA analysis**

The description of the cost items will follow the definitions made in the last report from the consultancy company BVG Associates[2] (BVGA) that provides strategy consulting in renewable energy for the UK Crown Estate and the Offshore Renewable Energy Catapult (January 2019). They introduce the cost concepts in a very clear way to avoid misunderstanding. The assumptions for that report are prepared for the conditions set below that we have adapted to our particular conditions:

The mentioned BVGA report assumed a **1GW project of 100, 10MW turbines located 60 km from shore in 30 m water depth and commencing operation in 2022.**

So, we have introduced over the general costs considered in that report, the following variations:

- We have transformed the figures of the BVGA report (2019) in pounds to €, with the average change in the first semester of 2019; 1€ approximately 0,884 lb or 1lb equal to 1,13 €.
- The report for the NORCOWE offshore bottom-fixed installation has been also considered, especially in relation with the meteocean conditions.

The list of cost items is the following (according to the BVGA report):

1. **Development and Project management**
   1.1. Development and consenting services
   1.2. Environmental surveys
   1.3. Resource and meteocean assessment
   1.4. Geological and hydrographical surveys
   1.5. Engineering and consultancy
2. **Wind turbine**
   2.1. Nacelle
   2.2. Rotor
   2.3. Tower
3. **Balance of Plant**
   3.1. Cables
   3.2. Turbine foundation
   3.3. Offshore substation
   3.4. Onshore substation
   3.5. Operating base
4. **Installation and Commissioning**
   4.1. Foundation installation
   4.2. Offshore substation installation
   4.3. Onshore substation installation
   4.4. Onshore export cable installation
   4.5. Turbine installation
   4.6. Construction port
   4.7. Offshore logistics
5. **Operation and maintenance services**
   5.1. Operations
   5.2. Maintenance and services
6. **Decommissioning**
   6.1. Turbine decommissioning
   6.2. Foundation decommissioning
   6.3. Substation decommissioning
   6.4. Decommissioning port
   6.5. Reuse, recycling and disposal (Excluded)

In relation to the lifetime, there are many definitions below, but we have considered the first one, the **functional life**;

- ***Functional Lifetime***: it is the period over which the functional activity of the asset is required.
- ***Physical Lifetime***: it is the period over which the asset is expected to last physically, till the replacement or major rehabilitations are physically required.
- ***Technological lifetime***: the period until technical obsolescence dictates replacement due to the development of a technologically superior alternative.
- ***Economic lifetime***: the period until economic obsolescence dictates replacement with a lower cost alternative.
- ***Social al and legal life:*** the period until human desire or legal requirement dictates replacement:

All the cost items described below can be included in the following categories:

- Research and Development (R&D) costs
- CAPEX. Capital expenditure is also known as fixed cost (a cost that does not change with an increase of decrease in the amount of goods or services produced or sold; namely, turbine, BOP, and financial cost (not included as the depreciation strategy could modify results).
- OPEX. Operational expenditure that covers all the costs paid after the windfarm take over point including operation costs and maintenance costs
- Disposal Costs is equivalent to decommissioning and can include reuse or recycling at the end of life (in our study, these two concepts were considered zero as there is no differences between the baseline and yaw scenarios).

## 4.5 LCCA Cost description

Herein, we roughly described what is included in each cost concept

### 1. Development and Project management

| | COST CONCEPT | |
|---|---|---|
| **1** | **DEVELOPMENT AND PROJECT MANAGEMENT** | |
| | **Function** | Development and project management covers the activities up to the point of financial close or placing firm orders to proceed with wind farm construction. This includes activities required to secure planning consents such as the environmental impact assessment, and activities required to define the design and engineering aspects. |
| | **What's in it** | Development and consenting services, Environmental surveys, Resource and meteocean assessment, Geological and hydrological surveys, Engineering and consultancy |
| **1.1.** | **Development and consenting services** | |
| | **Function** | Development and consenting covers the work needed to secure consent and manage the development process through to financial close. |
| | **What's in it** | Scoping. Assessment. Site-specific impacts. Mitigation. Residual impacts. Environmental Statement. Habitat regulations assessment |

| | | |
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| | | |
| **1.1.1** | **Environmental impact assessments** | |
| | **Function** | An EIA assesses the potential impact of the proposed development on the physical, biological and human environment during the construction, operation and decommissioning of the wind farm. |
| | **What's in it** | Scoping. Assessment. Site-specific impacts. Mitigation. Residual impacts. Environmental Statement. Habitat regulations assessment |
| **1.2** | **Environmental Surveys** | |
| | **Function** | An EIA assesses the potential impact of the proposed development on the physical, biological and human environment during the construction, operation and decommissioning of the wind farm. |
| | **What's in it** | Scoping. Assessment. Site-specific impacts. Mitigation Residual impacts. Environmental Statement. Habitat regulations assessment |
| **1.2.1** | **Benthic environmental surveys** | |
| | **Function** | Benthic studies survey species that live on the seabed and in sediment. The survey data and analysis is used to define areas of similar environmental conditions on the sea bed and to inform habitat and species impact studies |
| | **What's in it** | Species identification and counting, Laboratory analyses, Impact models and reports |
| **1.2.2** | **Fish and shellfish surveys** | |
| | **Function** | Fish and shellfish surveys establish what species are present in the water column within the proposed wind farm site and surrounding areas. The resulting data is used to inform impact analysis and reporting. |
| | **What's in it** | Species identification and counting, Laboratory analyses, Impact models and reports |
| **1.2.3** | **Ornithological environmental surveys** | |
| | **Function** | Ornithological surveys establish the presence and behavior of birds within the wind farm boundary and surrounding areas. The data from these bird surveys is used to establish the risks to birds that a wind farm may pose. |
| | **What's in it** | Species identification and counting, Impact models and reports |
| **1.2.4** | **Marine mammal environmental surveys** | |
| | **Function** | Marine mammal surveys establish the diversity, abundance, distribution and behavior of cetaceans (including porpoises, dolphins and whales) and seals within the wind farm boundary and surrounding areas. Surveys are typically undertaken monthly for at least two years to establish how these variables change across seasons and between years. The data from these surveys is used to establish the potential impacts to marine mammals that a wind farm may po |
| | **What's in it** | Offshore ornithological and mammal surveying vessels and craft<br>Species identification and counting, Impact models and reports |
| **1.2.5** | **Onshore environmental surveys** | |
| | **Function** | Onshore environmental surveys consider the potential ecological impact that cable-laying and onshore substations may have on the onshore environment. |
| | **What's in it** | Surveying. Data analysis. Reporting |
| **1.2.6** | **Human impact studies** | |
| | **Function** | Human impact studies assess the impact that a proposed wind farm may have on the community living in and around the coastal area near the wind farm. |

| | | |
|---|---|---|
| | **What's in it** | Surveys. Consultation |
| **1.3** | **Resource and meteocean assessment** | |
| | **Function** | Resource and meteocean assessment is carried out to provide atmospheric and oceanographic datasets to inform the engineering design of a wind farm, the potential future energy production, and to fully describe the likely operating conditions at the proposed wind farm location |
| | **What's in it** | Structure. Sensors. Maintenance |
| **1.3.1** | **Structure** | |
| | **Function** | The structure provides the mounting for the meteorological and meteocean, sensors and auxiliary systems plus safe access for personnel. |
| | **What's in it** | Foundation. Platform. Mast. Buoys |
| **1.3.2** | **Sensors** | |
| | **Function** | Sensors provide data on meteorological and oceanographic conditions at the site of interest. Data loggers provide data storage, processing and remote communications capability. |
| | **What's in it** | Meteorological sensors. Anemometers. Meteocean sensors. Data loggers |
| **1.3.3** | **Maintenance** | |
| | **Function** | Offshore wind and meteocean systems will require maintenance, including inspection, cleaning and refueling (where diesel generators or hydrogen fuel cells or similar are used). |
| | **What's in it** | Access vessel. Maintenance personnel. Equipment and consumables |
| **1.4.** | **Geological and hydrographical surveys** | |
| | **Function** | Seabed surveys analyses the sub seabed environment of the proposed wind farm site and export cable route to assess its geological condition and engineering characteristics. The data collected is utilized in a wide range of engineering and environmental studies through the design and development phase |
| | **What's in it** | Geophysical surveys. Geotechnical surveys. Hydrographic surveys |
| **1.4.1** | **Geophysical surveys** | |
| | **Function** | Geophysical surveys establish sea floor bathymetry, seabed features, water depth and soil stratigraphy, as well as identifying hazardous areas on the seafloor and manmade risks such as unexploded ordnance |
| | **What's in it** | Geophysical survey vessels |
| **1.4.2** | **Geotechnical surveys** | |
| | **Function** | Geotechnical site investigations are conducted following the geophysical survey to use the information obtained to target soil/rock strata boundaries and engineering properties or specific sea floor features. |
| | **What's in it** | Geotechnical survey vessels |
| **1.4.3** | **Hydrographic surveys** | |
| | **Function** | Hydrographic surveys examine the impact of the wind farm development on local sedimentation and coastal processes such as erosion. This is often part of the geophysical survey. These surveys are also part of the post construction monitoring during the operations phase. |
| | **What's in it** | Vessels. Crews. Survey equipment |

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| | | |
| **1.5** | **Engineering and consultancy** | |
| | **Function** | Front-end engineering and design (FEED) studies address areas of wind farm system design and develop the concept of the wind farm in advance of procurement, contracting and construction.<br>Earlier on in the process, pre-FEED studies are used to develop an outline concept of the project for the purposes for defining the consent envelope and to inform environmental impact studies.<br>The FEED study is continually refined through the development process and is ultimately used to frame and process substantial engineering and procurement decisions. |
| | **What's in it** | Layout design and optimization. Turbine selection. Foundation type selection. Electrical design strategy. Interface management. Health and safety planning. Installation methods. Operational strategy |

**Table 6. Description of Development and Project Management (BVGA[2])**

## 2. Turbine

| | | |
|---|---|---|
| **COST CONCEPT** | | |
| **2** | **TURBINE** | |
| | **Function** | The turbine converts kinetic energy from the wind into three-phase AC electrical energy. |
| | **What's in it** | Nacelle, Rotor and Power |
| **2.1.** | **Nacelle** | |
| | **Function** | The nacelle supports the rotor and converts the rotational energy from the rotor into three-phase AC electrical energy |
| | **What's in it** | Bedplate. Main bearing. Main shaft. Gearbox. Generator. Power take-off. Control system. Yaw system. Yaw bearing. Nacelle auxiliary systems. Nacelle cover. Small engineering components. Structural fasteners. Condition monitoring system |
| **2.1.1** | **Bedplate** | |
| | **Function** | The bedplate supports the drive train and the rest of the nacelle components and transfers loads from the rotor to the tower. |
| | **What's in it** | Large SG iron or fabricated steel structure Machining and painting |
| **2.1.2** | **Main Bearing** | |
| | **Function** | The main bearing supports the rotor and transfers some of the rotor loading to the nacelle bedplate |
| | **What's in it** | Forged rolled ring, machined and hardened Rolling elements (spherical, crowned cylindrical / tapered). Rolling element support (cage). Lubricants and seals SG iron bearing housing |
| **2.1.3** | **Main Shaft** | |
| | **Function** | The main shaft transfers torque from the rotor to the gearbox or, for some direct drive designs, the generator. It is supported at the rotor end by the main shaft bearing and at the other end either by the gearbox / generator or separately mounted bearing |

| | | |
|---|---|---|
| | **What's in it** | Forged / cast shaft Machining, NDT and painting |
| **2.1.4** | **Gearbox** | |
| | **Function** | Where used, a gearbox converts rotor torque at a speed of 5-15 rpm to a speed of up to about 600rpm for a medium speed gearbox and 1500rpm for a high-speed gearbox for conversion to electrical energy by the generator. |
| | **What's in it** | SG iron castings (including higher grade (say EN-CJS-700-2U) for items such as planned carrier) and steel forgings Cylindrical, taper and spherical roller bearings; plain bearings Gears Lubricants Sensors |
| **2.1.5** | **Generator** | |
| | **Function** | The generator converts mechanical energy to electrical energy. |
| | **What's in it** | Castings. Windings. Bearings Sensors. Slip rings for doubly fed induction generators High-speed shaft coupling |
| **2.1.6** | **Power take-off** | |
| | **Function** | The power take-off receives electrical energy from the generator and adjusts voltage and frequency for onward transfer to the wind farm distribution system. |
| | **What's in it** | Power converter. Transformer. Switchgear Cables |
| **2.1.7** | **Control System** | |
| | **Function** | The control system provides supervisory control (including health monitoring) and active power and load control in order to optimize wind turbine life and revenue generation, while meeting externally imposed requirements. |
| | **What's in it** | Control panels. Control system hardware and software Sensors: Accelerometers, load cells, power meters, strain gauges, thermocouples, and tachometers. Safety and emergency systems |
| **2.1.8** | **Yaw System** | |
| | **Function** | The yaw system orients the nacelle to the wind direction during operation. |
| | **What's in it** | Yaw motors and associated gearboxes Yaw brakes Sensors |
| **2.1.9** | **Yaw bearing** | |
| | **Function** | The yaw bearing connects the nacelle and tower, enabling the yaw system to orient the nacelle to any wind direction during operation. |
| | **What's in it** | Forged rings, machined, hardened and surface finished Balls Cages / spacers Seals Grease. Metal sprayed and/or painted finish |
| **2.1.10** | **Nacelle Auxiliary System** | |
| | **Function** | A number of auxiliary systems facilitate ongoing unattended operation of the wind turbine for the vast majority of the time, and support planned maintenance, which typically should be only on an annual basis |
| | **What's in it** | Brake Rotor lock Cooling Anemometry Fire protection UPS Internal service crane |
| **2.1.11** | **Nacelle Cover** | |
| | **Function** | The nacelle cover provides weatherproof protection to the nacelle components plus support and access to external components such as coolers, wind measurement equipment and lighting protection devices |
| | **What's in it** | Fiberglass or steel construction Built-in or post-assembled auxiliary systems (for example lighting) Maintenance support features |

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| **2.1.12** | **Small Engineering Components** | |
| | **Function** | A range of frequently standard engineering components makes up the rest of the nacelle assembly |
| | **What's in it** | Guards, flooring, drip trays, cable and hose handing systems and other fixed maintenance aids. Anti-vibration mounts Lightning conductors. Small fasteners and other accessories and consumables used during nacelle assembly |
| **2.1.13** | **Structural fasteners** | |
| | **Function** | Fasteners (either bolts or studs) are used in a range of critical bolted joints, for example connecting rotor to main shaft, main bearing housings to nacelle bedplate and yaw bearing to the underside of nacelle bedplate. |
| | **What's in it** | Bolts. Studs. Nuts |
| **2.1.14** | **Condition Monitoring System** | |
| | **Function** | Condition monitoring systems provide additional health checking and failure prediction capability |
| | **What's in it** | Sensors. Condition monitoring hardware and software |
| **2.2** | **Rotor** | |
| | **Function** | The rotor extracts kinetic energy from the air and converts this into rotational energy in the drive train. |
| | **What's in it** | Blades. Hub casting. Blade bearings. Pitch system. Spinner. Rotor auxiliary systems. Fabricated steel components. Structural fasteners. |
| **2.2.1** | **Blades** | |
| | **Function** | The blades capture the energy in the wind and transfer torque and other unwanted loads to the drive train and rest of the turbine |
| | **What's in it** | Structural composite materials. Blade root. Environmental protection. |
| **2.2.2** | **Hub casting** | |
| | **Function** | The hub connects the blades to the main shaft. |
| | **What's in it** | Casting. Non-destructive testing. Machining. Painting |
| **2.2.3** | **Blade bearings** | |
| | **Function** | The blade bearings enable adjustment of blade pitch angle to control power output from the turbine, minimize loads and start/stop turbine as required. |
| | **What's in it** | Forged rings, machined, hardened and surface finished Balls Cages / spacers. Seals. Grease. Metal sprayed and/or painted finish |
| **2.2.4** | **Pitch system** | |
| | **Function** | The pitch system adjusts the pitch angle of the blades to control power output from the turbine, minimize loads and start/stop turbine as required. |
| | **What's in it** | Hydraulic pitch system or electric pitch system |
| **2.2.5** | **Spinner** | |
| | **Function** | The spinner provides environmental protection to the hub assembly and access into the hub and blades for maintenance personnel. |

| | | |
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| | | |
| | **What's in it** | Fiberglass moldings. Fabricated steel support frame |
| **2.2.6** | **Rotor auxiliary systems** | |
| | **Function** | Auxiliary systems may be incorporated to lubricate bearings and provide condition monitoring and advanced control inputs. |
| | **What's in it** | Automatic lubrication system. Blade load measurement system. Maintenance support features |
| **2.2.7** | **Fabricated steel components** | |
| | **Function** | Fabrications are often required to stiffen the blade bearing support and provide a connection for hydraulic pitch system actuators. Other items are required for personnel protection, to facilitate access and maintenance activities and to provide a lightning path from the blades into the nacelle. |
| | **What's in it** | Steel fabrications. Surface treatment |
| **2.3** | **Tower** | |
| | **Function** | The tower is typically a tubular steel structure that supports the nacelle. It also provides access to the nacelle and houses electrical and control equipment. Also provides shelter and storage for safety equipment. |
| | **What's in it** | Steel. Tower internals |
| **2.3.1** | **Steel** | |
| | **Function** | Steel is the most commonly used material for the manufacture of towers. |
| | **What's in it** | Steel plate. Steel flanges. Surface finish |
| **2.3.2** | **Tower internals** | |
| | **Function** | The tower internals provide means of access, lighting and safety for maintenance and service personnel, plus means of transferring hand tools and components to the nacelle. They provide support for control and electrical cables and housing of switchgear, transformers and other elements of power take-off. Tower internals also provide storage for survival equipment. A tuned damper may be located at the top of the tower to aide damping of tower and structure resonances. |
| | **What's in it** | Personnel access and survival equipment. Tuned damper. Electrical system. Tower internal lighting. Coatings. |

**Table 7. Description of turbine cost concepts (BVGA[2])**

# 3. Balance of Plant

| **COST CONCEPT** | | |
|---|---|---|
| **3** | **BALANCE OF PLANT** | |
| | **Function** | The balance of plant includes all the components of the wind farm except the turbines, including transmission assets built as a direct result of the wind farm |
| | **What's in it** | Cables, Turbine foundation, Offshore substation, Onshore substation, Operations base. |

| | | |
|---|---|---|
| **3.1.** | **Cables** | |
| | **Function** | The cables deliver the power output from the wind turbines to the grid. |
| | **What's in it** | Export cable, Array cable, Cable protection |
| **3.1.1** | **Export cable** | |
| | **Function** | The export cable connects the offshore and onshore substations. |
| | **What's in it** | Cable core, Cable outer, Cable accessories, Cable jointing and testing |
| **3.1.2** | **Array cable** | |
| | **Function** | The array cable creates loops or individual strings connecting all wind turbines to the offshore substation |
| | **What's in it** | Conductor, Insulator, Electrical screen, Optical fiber cable, Mechanical and chemical protection |
| **3.1.3** | **Cable protection** | |
| | **Function** | Cable protection provides protection to cables at vulnerable locations, from the wave and tidal action and when the cable enters the wind turbine or offshore substation aperture or J-tubes. |
| | **What's in it** | J-tube seals, Bend restrictors, Bend stiffeners, Cable mattresses, Rock placement |
| **3.2.** | **Turbine Foundation** | |
| | **Function** | The foundation provides support for the wind turbine, transferring the loads from the turbine at the tower interface level (typically around 20m above water level) to the seabed where the loads are reacted. The foundation also provides the conduit for the electrical cables, as well as access for personnel from vessels. |
| | **What's in it** | Monopile, Jacket, floating, Transition piece, Corrosion protection, Scour protection [B.2.5] |
| **3.2.1** | **Jacket** | |
| | **Function** | The primary function of a jacket is to support the static and dynamic loads of the wind turbine by anchoring it firmly to the seabed using a set of pin piles. Secondary functions include supporting the wave loads on the jacket itself and enabling cable entry. A jacket foundation does not have a separate transition piece. The upper part of the jacket performs many of the functions of the transition piece. |
| | **What's in it** | Steel, lattice, Struts, Nodes, Pin piles, Protective coating |
| **3.2.2** | **Floating foundation** | |
| | **Function** | Floating structures to support the wind turbines of different types; Tension Leg Platform, Spar Buoy, Barge type, Semi-submersible (adding ballast to the bottom of the columns) |
| | **What's in it** | Floating structure, mooring system, anchoring system |
| **3.2.3** | **Transition piece** | |
| | **Function** | The transition piece provides the connection between the foundation and the tower, typically extending around 20m above mean sea level (MSL). It also supports secondary steelwork which provides functions such as allowing personnel access via a work platform, supporting cables and supporting the corrosion protection system |

| | | |
|---|---|---|
| | **What's in it** | Crew access system and work platform, Internal platforms, Davit crane, J-tubes, I-tube or monopile entry point |
| **3.2.4** | **Corrosion protection** | |
| | **Function** | Corrosion protection protects the foundation from corrosion to the extent that is required. |
| | **What's in it** | Paints and thermal metal spray coatings, Zinc or aluminum based sacrificial anodes, Impressed current cathodic protection systems |
| **3.2.5** | **Scour protection** | |
| | **Function** | Scour protection prevents scour of the seabed caused by the speed-up of water moving around the foundation, which safeguards the performance and integrity of the foundation. |
| | **What's in it** | Rock or geotextile sand containers |
| **3.3.** | **Offshore substation** | |
| | **Function** | Offshore substations are used to reduce electrical losses before export of power to shore. This is done by increasing the voltage, and in some cases converting from alternating current (AC) to direct current (DC). The substation also contains equipment to manage the reactive power consumption of the electrical system including the capacitive effects of the export cables. |
| | **What's in it** | Electrical system, Facilities, Structure |
| **3.3.1** | **Electrical system** | |
| | **Function** | The electrical system integrates AC power output from individual turbines and transforms voltage from for example 66kV to 275kV for export to onshore substation, else converts to DC for onward transmission |
| | **What's in it** | HVAC system or HVDC system |
| **3.3.2** | **Facilities** | |
| | **Function** | Auxiliary systems that support the operation and maintenance of the substation and enable some wider wind farm maintenance activities. |
| | **What's in it** | Auxiliary electrical systems, Monitoring systems, Communication system, Fire and blast protection system, Standby generator (normally for HVDC substations), Crane Control room & refuge, Clean and black water systems (normally for HVDC substations), Fuel tanks (normally for HVDC substations), Heating, ventilation and air conditioning equipment |
| **3.3.3** | **Structure** | |
| | **Function** | The structure provides support and protection for the electrical and other systems. |
| | **What's in it** | Helideck and/or Heli winch Steel structure |
| **3.4.** | **Onshore substation** | |
| | **Function** | The onshore substation transforms power to grid voltage, for example 400kV. Where a high voltage DC export cable, the substation will convert the power three phase AC. |
| | **What's in it** | Buildings, access and security |
| **3.4.1** | **Buildings, access and security** | |

| | | |
|---|---|---|
| | **Function** | Buildings, access and security provide physical protection and security for the onshore electrical equipment that connects the wind farm to the onshore transmission network |
| | **What's in it** | Monitoring systems, Auxiliary and low voltage system, Welfare facility |
| **3.5.** | **Operations base** | |
| | **Function** | The operations base supports the operation, maintenance and service of the wind farm. |
| | **What's in it** | Warehouse, Workshop, Vessel berths |

**Table 8. Description of the Balance of Plant cost concepts**

## 4. Installation And Commissioning

| | | |
|---|---|---|
| | **COST CONCEPT** | |
| **4** | **INSTALLATION AND COMMISSIONING** | |
| | **Function** | All installation and commissioning of balance of plant and turbines, including land- and sea-based activity. For offshore activities, the process starts by transporting components from the nearest port to manufacture to either the construction port or straight to site. Activities are complete at the wind farm construction works completion date, where assets are handed over to operational teams. |
| | **What's in it** | Foundation installation, Offshore substation installation, Onshore substation construction, Onshore export cable installation, Offshore cable installation, Turbine installation, Construction port, Offshore logistics. |
| **4.1.** | **Foundation installation** | |
| | **Function** | Foundation installation consists of the transport and fixing of foundation in position |
| | **What's in it** | Foundation installation vessel |
| **4.1.1** | **Foundation installation vessel** | |
| | **Function** | The foundation installation vessel transports the foundations from the quayside fabrication facility or construction port to the site and secures them to the seabed or floating. Heavy lift vessels, floating sheerleg vessels and self-propelled jack-up vessels are all used. |
| | **What's in it** | Foundation handling equipment, Foundation installation equipment, Sea fastenings, Crane Auxiliary cranes Dynamic positioning system Propulsion systems Jack-up system Spud cans Helideck Gangway |
| **4.2.** | **Offshore substation installation** | |
| | **Function** | The installation of the offshore substation consists of the transfer of the substation from its quayside fabrication site and the installation on the foundation. |
| | **What's in it** | Substation installation vessel |
| **4.2.1** | **Substation installation vessel** | |
| | **Function** | The substation installation vessel allows the transport and lift of offshore substation, in order to position it on pre-installed foundation. |

| | | |
|---|---|---|
| | **What's in it** | Crane, Auxiliary cranes, Dynamic positioning system, Propulsion systems, Helideck, Gangway |
| **4.3.** | **Onshore substation construction** | |
| | **Function** | The construction of the onshore substation consists of the construction of the infrastructure and the installation of electrical equipment |
| | **What's in it** | Civil works, Electrical works |
| **4.4.** | **Onshore export cable installation** | |
| | **Function** | The installation of the onshore export cable completes the connection between the offshore export cable and the onshore substation. |
| | **What's in it** | Drilling equipment, Trenching equipment, Cable-laying equipment |
| **4.5.** | **Offshore cable installation** | |
| | **Function** | The installation of array cables enables the connection of the wind turbines to the offshore substation whilst the installation of the export cable enables the connection between the offshore and onshore substations. |
| | **What's in it** | Cable-laying vessel |
| **4.5.1** | **Cable-laying vessel** | |
| | **Function** | The cable-laying vessel lays the cables between the wind turbines and offshore substation and between the offshore and onshore substation. |
| | **What's in it** | ROV, Cable-handling equipment, Crane, Personal transfer gangway |
| **4.5.2** | **Cable burial** | |
| | **Function** | The cable is buried to a predefined depth under the seabed to ensure protection from external aggression (for example fishing and anchoring) as well as to prevent exposure due to seabed mobility. |
| | **What's in it** | Cable burial vessel, Cable plough, Trenching ROV, Vertical injector |
| **4.5.3** | **Cable pull-in** | |
| | **Function** | For the array cable, the pull-in consists of the pulling of the cable into the substation or turbine foundation. For export cables, the pull-in consists of pulling the cable to shore as well as into the substation |
| | **What's in it** | Barge Amphibious vehicle, ROV, Messenger wire, J-tubes, Horizontal directional drilling, Winches, Quadrant Floats |
| **4.5.4** | **Electrical testing and termination** | |
| | **Function** | The electrical testing is designed to test and prove cable integrity whilst the termination enables the electrical connection between the offshore cable and either the wind turbine, the substation or the onshore cables. |
| | **What's in it** | Test and diagnostics device, Connection cables, Power supply, Termination plug, Cable trays, Hang-off clamp |
| **4.6.** | **Turbine installation** | |
| | **Function** | Turbine installation involves transportation of the turbine components from the construction port and installation of the turbine components onto the foundation. |
| | **What's in it** | Turbine installation vessel, Commissioning |
| **4.6.1** | **Turbine installation vessel** | |

| | | |
|---|---|---|
| | **Function** | The turbine installation vessel transports the turbine components to site and supports the erection of the turbine on the foundation. Similar jack-up vessels are used to those for foundation installation. |
| | **What's in it** | Turbine handling equipment and sea fastenings, Crane, Auxiliary cranes, Dynamic positioning system, Propulsion systems, Jack-up system, Spud cans, Helideck, Gangway |
| **4.6.2** | **Commissioning** | |
| | **Function** | After installation, commissioning is the process of safely completing mechanical and electrical assembly, putting all systems to work and addressing punch lists before handover |
| | **What's in it** | Electrical testing device, Generator |
| **4.7.** | **Construction port** | |
| | **Function** | The construction port is the base for pre-assembly and construction of the wind farm. Separate locations may be used for feeding foundations and the wind turbines to a wind farm. Location is critical as it affects the time spent in shipment and sensitivity to weather windows. |
| | **What's in it** | Quay, Lay-down area, Cranes, Workshops Personnel facilities |
| **4.8.** | **Offshore logistics** | |
| | **Function** | Offshore logistics involves coordination and support of offshore installation and commissioning activities |
| | **What's in it** | Sea-based support, Marine coordination, Weather forecasting and meteocean data |
| **4.8.1** | **Sea-based support** | |
| | **Function** | A number of vessels are used to support the installation process. These may include CTVs, anchor handling, barges, dive support and ROV handling vessels |
| | **What's in it** | CTV, Barge, ROV |
| **4.8.2** | **Marine coordination** | |
| | **Function** | Marine coordination is necessary in order to manage heightened marine traffic as well as multi-vessel activity on an offshore construction site. |
| | **What's in it** | Marine management system software, Marine coordination centre |
| **4.8.3** | **Weather forecasting and meteocean data** | |
| | **Function** | Weather forecasts are needed for short-term planning of offshore activities (for example vessel transfers and lifts) and the closer the forecast is to the activity, the more reliable it gets. Meteocean data recordings are used to provide real time data to support offshore activity, to verify forecast tools and to resolve disputes regarding weather downtime. Key meteocean parameters that impact installation and commissioning activities are wind speed, wave height and current. |
| | **What's in it** | Weather forecast report (and online access), Wave buoy, Current meter, Lidar, Anemometer |

**Table 9. Installation and Commissioning Costs concepts (BVGA[2])**

# 5. Operation And Maintenance

| | | |
|---|---|---|
| | **COST CONCEPT** | |
| **5** | **OPERATION AND MAINTENANCE** | |
| | **Function** | Operation, maintenance and service (OMS) are the combined functions which, during the lifetime of the wind farm, support the ongoing operation of the wind turbines, balance of plant and associated transmission assets. OMS activities formally start at the wind farm construction works completion date.<br>The focus of these activities during the operational phase is to ensure safe operations, to maintain the physical integrity of the wind farm assets and to optimize electricity generation. |
| | **What's in it** | Operations, Maintenance and service |
| **5.1.** | **Operations** | |
| | **Function** | Operations relate to management of the asset such as health and safety, control and operation of the asset including wind turbines and balance of plant, remote site monitoring, environmental monitoring, electricity sales, administration, marine operations supervision, operation of vessels and quayside infrastructure, and back office tasks. |
| | **What's in it** | Training, Onshore logistics, Offshore logistics, Health and safety inspections |
| **5.1.1** | **Training** | |
| | **Function** | Training ensures that OMS personnel are qualified to fulfil the roles needed by the wind farm while ensuring their own safety and those of colleagues. |
| | **What's in it** | Training courses, Training examinations, Certification |
| **5.1.2** | **Onshore logistics** | |
| | **Function** | Onshore logistics involves support and resources to the wind farm operations, including quayside infrastructure, warehousing, logistics and operational planning. |
| | **What's in it** | Facilities management |
| **5.1.3** | **Offshore logistics** | |
| | **Function** | Offshore logistics involves management and coordination of all marine based activities and operations |
| | **What's in it** | Crew transfer vessels, Service operation vessels, Turbine access systems, Helicopters , Weather forecasting and meteocean data ,Marine planning software Communications equipment including radio and asset tracking Safety planning and systems |
| **5.1.4** | **Health and safety inspections** | |
| | **Function** | Health and safety inspections are a crucial activity to ensure the ongoing safe operation of wind farm infrastructure and systems, and to fulfil statutory obligations to inspect safety critical systems on a regular basis. |
| | **What's in it** | Health and safety equipment |
| **5.2.** | **Maintenance and service** | |

| | | |
|---|---|---|
| | **Function** | Maintenance and service activities ensure the ongoing operational integrity of the wind turbines and associated balance of plant, including planned maintenance and unplanned service in response to faults, either proactive or reactive. |
| | **What's in it** | Turbine maintenance and service, Balance of plant maintenance and service |
| **5.2.1** | **Turbine maintenance and service** | |
| | **Function** | Effective turbine maintenance and service ensures the long-term productivity of the turbines. |
| | **What's in it** | Blade inspection and repair, Nacelle component refurbishment, replacement and repair, Electrical transmission system maintenance |
| **5.2.2** | **Blade inspection and repair** | |
| | **Function** | Blade inspection and repair consists of the inspection of the condition of blades and replacing or repairing blades in a timely and cost-effective manner. |
| | **What's in it** | Unmanned aerial vehicle |
| **5.2.3** | **Main component refurbishment, replacement and repair** | |
| | **Function** | Main component refurbishment, replacement and repair consists of the replacement of large components such as gearboxes, blades, transformers and generators in a timely and cost-effective manner |
| | **What's in it** | Large component repair vessel |
| **5.3.** | **Balance of plant maintenance and service** | |
| | **Function** | Balance of plant maintenance and service is focused on ensuring the operational integrity and reliability of all wind farm assets other than the wind turbines, including the substation(s), foundations, array cables, export cables, scour protection and corrosion protection systems. |
| | **What's in it** | Foundation inspection and repair, Cable inspection and repair, Scour monitoring and management, Substation maintenance and service |
| **5.3.1** | **Foundation inspection and repair** | |
| | **Function** | Foundation inspection and repair identifies and addresses corrosion and structural problems above and below the water line. |
| | **What's in it** | Remotely operated vehicle, Autonomous underwater vehicle |
| **5.3.2** | **Cable inspection and repair** | |
| | **Function** | Identify faults and replace whole or sections of cable. |
| | **What's in it** | Maintenance and service record management |
| **5.3.3** | **Scour monitoring and management** | |
| | **Function** | Mitigates the risk of undermining seabed movements on subsea structures. |
| | **What's in it** | Seabed inspection |
| **5.3.4** | **Substation maintenance and service** | |
| | **Function** | Ensures there is no interruption to transmission from electrical failures or structural problems with the offshore platform. |
| | **What's in it** | Inspection, Maintenance and service record management |

**Table 10. Operation and Maintenance Costs Concepts (BVGA[2])**

# 6. Decommissioning

| | | COST CONCEPT |
|---|---|---|
| 6 | DECOMMISSIONING | |
| | Function | Removal or making safe of offshore infrastructure at the end of its useful life, plus disposal of equipment |
| | What's in it | Turbine decommissioning, Foundation decommissioning, Cable decommissioning, Substation decommissioning, Decommissioning port, Reuse, recycling or disposal, Environmental surveys |
| 6.1. | Turbine decommissioning | |
| | Function | Complete removal and shipment to shore of turbine rotor, nacelle and tower. |
| | What's in it | Turbine decommissioning |
| 6.2. | Foundation decommissioning | |
| | Function | Removal and shipment to shore or cut-off at seabed level and making safe. |
| | What's in it | Foundation decommissioning |
| 6.3. | Cable decommissioning | |
| | Function | Removal and shipment to shore. |
| | What's in it | Cable decommissioning |
| 6.4. | Substation decommissioning | |
| | Function | Decommissioning plans typically are required as part of gaining approval to construct. These may define specific requirements for removal of components below the mud line which in turn may drive the choice or design of substation foundations and installation methods. |
| | What's in it | Substation decommissioning |
| 6.5. | Decommissioning port | |
| | Function | Port where equipment removed is offloaded and marshalled for next stage of processing |
| | What's in it | Decommissioning port |
| 6.5. | Reuse, recycling or disposal | |
| | Function | Once equipment is onshore, there is a motivation to extract maximum value via reuse, recycling or disposal. |
| | What's in it | Reuse, recycling or disposal |

**Table 11. Decommissioning Cost Concepts**

## 4.6 LCCA Calculations

### 4.6.1 Strategy for the Cost items description

All the project analysis described in the next tables below ([12] to [23]), will point out the differences among the two scenarios. We include in the next chart the main parameters of the two scenarios considered and the wind farms main features taken as reference.

| Main Features | Data Sources BVG Associate Report | Data Source NORCOWE Report | Base Offshore Bottom-Fix BASELINE | Improved Offshore Bottom-Fix YAW |
|---|---|---|---|---|
| **Nº Turbines (units)** | 100 | 80 | 80 | 80 |
| **Nominal Capacity (MW)** | 10 | 10 | 10 | 10 |
| **WF Total Power (MW)** | 1,000 | 800 | 800 | 800 |
| **Dept** | 30 | 23 | 23 | 23 |
| **Distance to shore** | 60 | 80 | 80 | 80 |
| **Foundation** | Jacket or monopile | Monopiles | Jacket | Jacket |
| **Control** | Non-control | Non-Control | Greedy Control | Yaw-Control |
| **Area (meteocean)** | Indistintive | North Germany | North Germany | North Germany |

**Table 12. Main features of selected scenarios (green) and referenced Wind Farms (blue)**

We have developed an excel spreadsheet with four main tabs that highlight key results and some additional supporting those main tabs with some explanations on the way the calculations were done. Main tabs are the following

- **LCC-Offs-BASE**. It is a complete LCC with the information of the **base scenario** (bottom-fixed offshore wind farm with non-controlled strategy)
- **LCC-Offs-YAW** A complete LCC with the information of the yaw scenario (bottom-fixed offshore wind farm with the yaw-controlled strategy)
- **Comparison**. All results are displayed in parallel columns (for BASE and YAW). Then, a table is also included with the summary of results (Non-Discounted and Discounted).
- **LCOE.** It is the calculation for the two scenarios in a single page considering the Net Energy Productions

The auxiliary tabs are:

- **Boundary**. A sheet where the input information of each scenario is included.
- **BVGA**. Include the precursor information of the BVG Associates report 2019 (in lb) that was taken as reference in many chapters.
- **Cables & Jacket.** Information of cable costs provided by Ramboll and calculation of jackets based in BVGA data.
- **Installation**. Details for installations costs based on cable tab and adaptations from the author.
- **O&M Base and Yaw**. Some analysis to define the O&M costs in the two first scenarios

Hereinafter, we highlight in a red frame, those bullets where there are significative differences among scenarios, keeping equal those other cost categories which are the same in both cases. Thus, we present these combined tables highlighting the differences and provide then, the explanations to understand such differences.

### 4.6.2 Cost items comparison.

#### 1. CAPEX. DEVELOPMENT AND PROJECT MANAGEMENT

There will be almost no variations in this cost category between both scenarios. However, we do believe that the design of the software for the installation, will introduce some more complexity considering the new control system. We have estimated a 0,5% additionally to the calculated Engineering costs of the base case. That is approximately EUR 20.000 in addition.

Development and consenting, environmental surveys, resources and meteocean assessment and geological and hydrographical surveys will be the same for both options.

In the next table, we compare the figures as described. Framed in red the concept that varies (Engineering studies). The costs categories have been taken from the BVGA 2019 report, with the corresponding adaptations (mainly adapting the number of turbines and converting sterling pounds to euros.

| A. CAPEX (Capital Costs) | | BASE | YAW |
|---|---|---|---|
| 1 | DEVELOPMENT AND PROJECT MANAGEMENT | 63,280,000 € | 63,298,080 € |
| 1.1 | Development and consenting services | 45,200,000 € | 45,200,000 € |
| 1.1.1 | Environmental impact assessments | 7,232,000 € | 7,232,000 € |
| 1.1.2 | Consent and development | 37,968,000 € | 37,968,000 € |
| 1.2 | Environmental Surveys | 3,616,000 € | 3,616,000 € |
| 1.2.1 | Benthic environmental surveys | 271,200 € | 271,200 € |
| 1.2.2 | Fish and shellfish surveys | 271,200 € | 271,200 € |
| 1.2.3 | Ornithological environmental surveys | 994,400 € | 994,400 € |
| 1.2.4 | Marine mammal environmental surveys | 994,400 € | 994,400 € |
| 1.2.5 | Onshore environmental surveys | 632,800 € | 632,800 € |
| 1.2.6 | Human impact studies | 452,000 € | 452,000 € |
| 1.3 | Resource and metocean assessment | 3,616,000 € | 3,616,000 € |
| 1.3.1 | Structure | 2,712,000 € | 2,712,000 € |
| 1.3.2 | Sensors | 587,600 € | 587,600 € |
| 1.3.3 | Maintenance | 316,400 € | 316,400 € |
| 1.4. | Geological and hydrographical surveys | 7,232,000 € | 7,232,000 € |
| 1.4.1 | Geophysical surveys | 1,356,000 € | 1,356,000 € |
| 1.4.2 | Geotechnical surveys | 5,424,000 € | 5,424,000 € |
| 1.4.3 | Hydrographic surveys | 452,000 € | 452,000 € |
| 1.5 | Engineering and consultancy | 3,616,000 € | 3,634,080 € |

**Table 13. Development and project management cost comparison**

## 2. Capex. Turbine

Herein, the comparative tables for the "Turbine" cost category.

| A. CAPEX (Capital Costs) | | BASE | YAW |
|---|---|---|---|
| 2 | TURBINE (100 units) | 480,747,200 € | 481,651,200 € |
| 2.1 | Nacelle | 289,280,000 € | 290,184,000 € |
| 2.1.1 | Bedplate | 14,464,000 € | 14,464,000 € |
| 2.1.2 | Main Bearing | 14,464,000 € | 14,464,000 € |
| 2.1.3 | Main Shaft | 14,464,000 € | 14,464,000 € |
| 2.1.4 | Gearbox | 50,624,000 € | 50,624,000 € |
| 2.1.5 | Generator | 72,320,000 € | 72,320,000 € |

| | | | |
|---|---|---|---|
| 2.1.6 | Power take-off | 50,624,000 € | 50,624,000 € |
| 2.1.7 | Control System | 18,080,000 € | 18,984,000 € |
| 2.1.8 | Yaw System | 12,294,400 € | 12,294,400 € |
| 2.1.9 | Yaw bearing | 5,062,400 € | 5,062,400 € |
| 2.1.10 | Nacelle Auxiliary System | 5,062,400 € | 5,062,400 € |
| 2.1.11 | Nacelle Cover | 7,232,000 € | 7,232,000 € |
| 2.1.12 | Small Engineering Components | 18,080,000 € | 18,080,000 € |
| 2.1.13 | Structural fasteners | 5,062,400 € | 5,062,400 € |
| 2.1.14 | Condition Monitoring System | 1,446,400 € | 1,446,400 € |
| **2.2** | **Rotor** | **136,684,800 €** | **136,684,800 €** |
| 2.2.1 | Blades | 94,016,000 € | 94,016,000 € |
| 2.2.2 | Hub casting | 10,848,000 € | 10,848,000 € |
| 2.2.3 | Blade bearings | 14,464,000 € | 14,464,000 € |
| 2.2.4 | Pitch system | 7,232,000 € | 7,232,000 € |
| 2.2.5 | Spinner | 1,446,400 € | 1,446,400 € |
| 2.2.6 | Rotor auxiliary systems | 2,892,800 € | 2,892,800 € |
| 2.2.7 | Fabricated steel components | 5,785,600 € | 5,785,600 € |
| **2.3** | **Tower** | **54,782,400 €** | **54,782,400 €** |
| 2.3.1 | Steel | 54,240,000 € | 54,240,000 € |
| 2.3.2 | Tower internals | 542,400 € | 542,400 € |

**Table 14. Turbine category cost comparison**

According to deliverable D4.5 "O&M Costs" conclusions, turbines will not be modified due to the new software. The impact of the wake redirection in one of the Wind farm turbines is negligible to modify the constituent elements, thus all the internal and external elements will be kept the same. The only difference is the control system, as some new gauges are needed, and the cost of the software will be slightly increased. The way the new algorithms will be sold is still unknown but maybe there will be an increase in the fix price when buying it and some maintenance will be considered. In our estimations, we add around 5% in extra costs (approximately €1 Million added). The final instrumentation is not simple to define and depends on the windfarm layout. Some partners consider there will be additional instrumentation costs (maybe one or two extra LIDAR and some more precise gauges than standard) although some others consider there won't be any additional investment. By prudence criteria we have established this extra 5% on this concept

## 3. CAPEX. BALANCE OF PLANT

| A. CAPEX (Capital Costs) | | BASE-FIX | YAW |
|---|---|---|---|
| **3** | **BALANCE OF PLANT** | **498,677,255 €** | **498,677,255 €** |
| **3.1.** | **Cables** | **214,645,478 €** | **214,645,478 €** |
| 3.1.1 | Export Cable | 134,844,878 € | 134,844,878 € |
| 3.1.2 | Array cable | 77,992,600 € | 77,992,600 € |
| 3.1.3 | Dynamic cable | 0 € | 0 € |

| | | | |
|---|---|---|---|
| 3.1.4 | Cable Protection | 1,808,000 € | 1,808,000 € |
| **3.2** | **Turbine Foundation** | **179,393,778 €** | **179,393,778 €** |
| 3.2.1 | Jacket | 143,233,778 € | 143,233,778 € |
| 3.2.2 | Floating structure | 0 € | 0 € |
| 3.2.3 | Mooring | 0 € | 0 € |
| 3.2.4 | Anchoring | 0 € | 0 € |
| 3.2.5 | Transition piece | 0 € | 0 € |
| 3.2.6 | Corrosion protection | 27,120,000 € | 27,120,000 € |
| 3.2.7 | Scour protection (not in floating) | 9,040,000 € | 9,040,000 € |
| **3.3** | **Offshore substations (1)** | **72,320,000 €** | **72,320,000 €** |
| 3.3.1 | Electrical System (HVAC) | 24,106,667 € | 24,106,667 € |
| 3.3.2 | Facilities | 12,053,333 € | 12,053,333 € |
| 3.3.3 | Structure | 36,160,000 € | 36,160,000 € |
| **3.4** | **Onshore substation (1)** | **28,928,000 €** | **28,928,000 €** |
| 3.4.1 | Building, access and security | 9,040,000 € | 9,040,000 € |
| 3.4.2 | Rest onshore substation | 19,888,000 € | 19,888,000 € |
| **3.5** | **Operation base** | **3,390,000 €** | **3,390,000 €** |

**Table 15. Balance of Plant Category cost comparison**

The new control system will not introduce any modification in the Balance of Plant section.

## 4. CAPEX. INSTALLATION AND COMMISSIONING

| A. CAPEX (Capital Costs) | | BASE | YAW |
|---|---|---|---|
| **4** | **INSTALLATION AND COMMISSIONING** | **462,358,710 €** | **462,358,710 €** |
| **4.1.** | **Foundation Installation** | **135,600,000 €** | **135,600,000 €** |
| 4.1.1 | Foundation Installation vessel | 54,240,000 € | 54,240,000 € |
| 4.1.2 | Foundation handling equipment | 43,392,000 € | 43,392,000 € |
| 4.1.3 | Foundation Installation equipment | 37,968,000 € | 37,968,000 € |
| **4.2** | **Offshore substation Installation** | **45,200,000 €** | **45,200,000 €** |
| 4.2.1 | Substation installation vessel | 14,916,000 € | 14,916,000 € |
| 4.2.2 | Semisubmesible vessels | 34,804,000 € | 34,804,000 € |
| **4.3** | **Onshore substation installation** | **22,600,000 €** | **22,600,000 €** |
| **4.4** | **Onshore export cable installation** | **63,387,350 €** | **63,387,350 €** |
| **4.5** | **Offshore cable installation** | **147,207,360 €** | **147,207,360 €** |
| 4.5.1 | Cable-laying and burial vessel | 107,461,373 € | 107,461,373 € |
| 4.5.2 | Dynamic cable installation | 0 € | 0 € |
| 4.5.3 | Cable pull-in | 10,304,515 € | 10,304,515 € |

| | | | |
|---|---|---|---|
| 4.5.4 | Electrical testing and termination | 14,720,736 € | 14,720,736 € |
| **4.6** | **Turbine installation** | **45,200,000 €** | **45,200,000 €** |
| 4.6.1 | Turbine installation/Comissioning | 45,200,000 € | 45,200,000 € |
| **4.7** | **Construction port (included inst. contract)** | **0 €** | **0 €** |
| **4.8** | **Offshore logistics (transport)** | **3,164,000 €** | **3,164,000 €** |
| 4.8.1 | Sea-based support | 2,246,440 € | 2,246,440 € |
| 4.8.2 | Marine coordination | 632,800 € | 632,800 € |
| 4.8.3 | Weather forecasting and meteocean data | 284,760 € | 284,760 € |

**Table 16. Installation and Commissioning. Costs comparison**

The installation will not be affected by the new control system. There will be maybe some extra LIDAR equipment, which are relatively costly, but it is not clear at this stage, how many of them will be needed (in case they were needed). Anyway, even with one or two LIDAR, the installation costs will not vary substantially (equipment costs are considered in the previous category cost).

# 5. OPEX. Operation And Maintenance

This is the concept where the biggest variations are shown. The yaw redirection modifies the wind received by the turbines in first and especially successive lines. Following the analysis of deliverable D4.5 "O&M Costs", the effects produced are; in one hand, the loads are on average increased in the wind farm, what generates an increase in the failure rates (the turbines increase the free stream received and consequently the loads in the constitutive elements). However, the wind received presents a higher quality (with less turbulences and more wind speed) raising the average energy output (improved AEP-Annual Energy Production) of the Wind Farm to a certain extend. The failure rates modification increases the Operation and Maintenance activities as more repairs must be done. A new repair or replacement implies spare parts, time of technicians and use of very expensive ships (like Jack-up vessels) that needs to be mobilised and demobilised. All the calculations were included in deliverable D4.5 and the results transferred to this section (please read it for further information).

The following table reproduces the differences in failure rates according to the average done by Qi Energy from the calculations done by Ramboll, Ikerlan and TNO in deliverable D4.5. These failures rates are the base for the calculation of the Maintenance costs presented later.

| FAILURE RATE COMPARISON | Minor Failure | | Major Failure | | Replacement | |
|---|---|---|---|---|---|---|
| | BASE | YAW | BASE | YAW | BASE | YAW |
| Gearbox | 0.6440 | 0.6475 | 0.1570 | 0.1579 | 0.0280 | 0.0282 |
| Generator | 0.0490 | 0.0490 | 0.0180 | 0.0180 | 0.0080 | 0.0080 |
| Main shaft | 0.2310 | 0.2362 | 0.0260 | 0.0266 | 0.0090 | 0.0092 |
| Power electrical system | 0.3700 | 0.3700 | 0.0430 | 0.0430 | 0.0020 | 0.0020 |
| Yaw system | 0.2590 | 0.2590 | 0.0360 | 0.0360 | 0.0120 | 0.0120 |
| Pitch system | 0.3970 | 0.3970 | 0.0200 | 0.0200 | 0.0080 | 0.0080 |
| Blades | 0.2000 | 0.2024 | 0.0450 | 0.0455 | 0.0400 | 0.0405 |

**Table 17. Failure Rates comparison for the Base and Yaw scenarios**

In the next two tables, we include the summary of the maintenance costs for the two scenarios, classified by unplanned and planned activities. The biggest cost category is associated to the use of vessels, especially those of large size like the Jack up vessels with very high rental and mobilization costs. Please for further details, revise D45 O&M Costs.

| BASELINE | | | |
|---|---|---|---|
| **Maintenance Costs** | **DISCOUNTED** | **UNDISCOUNTED** | **UNDISC/YEAR** |
| **Unplanned** | 589,802,996 € | 1,013,349,074 € | 40,533,963 € |
| Material | 31,147,935 € | 53,515,719 € | 2,140,629 € |
| Vessels | 469,475,793 € | 806,613,162 € | 32,264,526 € |
| Mob/Demobilization | 54,921,270 € | 94,361,030 € | 3,774,441 € |
| Crew | 34,257,999 € | 58,859,164 € | 2,354,367 € |
| **Planned** | 19,227,578 € | 33,035,180 € | 1,321,407 € |
| Material | 5,033,397 € | 8,647,953 € | 345,918 € |
| Vessels | 4,530,058 € | 7,783,158 € | 311,326 € |
| Crew | 9,664,123 € | 16,604,070 € | 664,163 € |
| **Total Direct Costs** | **609,030,574 €** | **1,046,384,255 €** | **41,855,370 €** |

**Table 18. Baseline maintenance costs.**

| YAW | | | |
|---|---|---|---|
| **Maintenance Costs** | **DISCOUNTED** | **UNDISCOUNTED** | **UNDISC/YEAR** |
| **Unplanned** | 592,096,815 € | 1,016,451,229 € | 40,658,049 € |
| Material | 31,457,487 € | 54,002,996 € | 2,160,120 € |
| Vessels | 471,056,506 € | 808,661,611 € | 32,346,464 € |
| Mob/Demobilization | 54,967,840 € | 94,363,163 € | 3,774,527 € |
| Crew | 34,614,982 € | 59,423,459 € | 2,376,938 € |
| **Planned** | 19,247,847 € | 33,042,734 € | 1,321,709 € |
| Material | 5,038,703 € | 8,649,930 € | 345,997 € |
| Vessels | 4,534,833 € | 7,784,937 € | 311,397 € |
| Crew | 9,674,310 € | 16,607,866 € | 664,315 € |
| **Total Direct Costs** | **611,344,661 €** | **1,049,493,962 €** | **41,979,758 €** |

**Table 19. Yaw-controlled maintenance costs**

The table ahead summarises all the costs variations, considering also Operation activities. The main categories of variations are:

- Overheads differs a bit as they are a percentage (15%) of the direct costs of O&M

- Personnel for maintenance, which are slightly increased due to the extra activities generated by the addition of repairs and replacements (failure rates increased).

Material and mobilization costs for maintenance. More repairs and replacement bring extra material costs and additional mobilization and demobilization activities.

| B. OPEX (Operational Costs) | | BASE | YAW |
|---|---|---|---|
| 5 | OPERATION, MAINTENANCE AND SERVICE | 1,286,897,125 € | 1,291,006,916 € |
| 5.1 | Operations | 240,512,871 € | 241,512,954 € |
| 5.1.1 | Personnel Costs | 6,894,867 € | 6,894,867 € |
| 5.1.2 | Training Personnel | 11,300,000 € | 11,300,000 € |
| 5.1.3 | Onshore logistics | 10,170,000 € | 10,170,000 € |
| 5.1.4 | Offshore logistics | 36,160,000 € | 36,160,000 € |
| 5.1.5 | Overheads | 53,948,004 € | 54,948,087 € |
| 5.1.6 | Health and safety inspections | 9,040,000 € | 9,040,000 € |
| 5.1.7 | Insurance | 113,000,000 € | 113,000,000 € |
| 5.2 | Maintenance and service | 1,046,384,255 € | 1,049,493,962 € |
| 5.2.1 | Personnel Costs | 75,463,233 € | 76,031,325 € |
| 5.2.2 | Material Costs | 62,163,672 € | 62,652,926 € |
| 5.2.3 | Mobilization Costs + Vessels rental | 908,757,350 € | 910,809,712 € |

**Table 20. Operation Costs. Cost comparison.**

## 6. Capex. Decommissioning

Decommissioning is the inverse process to remove or making safe of offshore infrastructure at the end of its useful life, plus disposal of equipment. We have not valued this last process although the excel tool is prepared to add that information and recalculate LCOE

| C. DECOMMISSIONING | | BASE | YAW |
|---|---|---|---|
| 6 | DECOMMISSIONING | 271,200,000 € | 271,200,000 € |
| 6.1 | Turbine decommissioning | 36,160,000 € | 36,160,000 € |
| 6.2 | Foundation decommissioning | 63,280,000 € | 63,280,000 € |
| 6.3 | Cable decommissioning | 126,560,000 € | 126,560,000 € |
| 6.4 | Substation decommissioning | 45,200,000 € | 45,200,000 € |
| 6.5 | Reuse, recycling or disposal | 0 € | 0 € |

**Table 21. Decommissioning**

## 7. Summary Table.

In the next table, we include a summary of the main results comparing the “base” scenario with the “yaw” scenario. The differences in costs (including O&M) are rather low. The data are shown in discounted (Present Value) and undiscounted values. The parameters taken for these calculations, as said are the following:

| | | |
|---|---|---|
| WACC real | % | 5.19% |
| Inflation Rate | % | 2.00% |
| Years of analysis | Nº | 26 |

**Table 22. Parameters to calculate Present Value.**

We have considered 25 years of operation and one additional year for decommissioning. The comparative tables are the following:

| LIFE CYCLE COSTING | BASE | | | YAW | | |
|---|---|---|---|---|---|---|
| COMPARISON | AMOUNT | AMOUNT/MW | % | AMOUNT | AMOUNT/MW | % |
| Development & PM | 63,280,000 € | 79,100 | 2.07% | 63,298,080 € | 79,123 | 2.06% |
| Turbine | 480,747,200 € | 600,934 | 15.69% | 481,651,200 € | 602,064 | 15.70% |
| Cables | 214,645,478 € | 268,307 | 7.01% | 214,645,478 € | 268,307 | 7.00% |
| Foundation | 179,393,778 € | 224,242 | 5.86% | 179,393,778 € | 224,242 | 5.85% |
| Substations and base | 104,638,000 € | 130,798 | 3.42% | 104,638,000 € | 130,798 | 3.41% |
| Installation | 462,358,710 € | 577,948 | 15.09% | 462,358,710 € | 577,948 | 15.07% |
| Decommissioning | 271,200,000 € | 339,000 | 8.85% | 271,200,000 € | 339,000 | 8.84% |
| **TOTAL CAPEX** | **1,776,263,165 €** | **2,220,329** | **57.99%** | **1,777,185,245 €** | **2,221,482** | **57.92%** |
| Operation | 240,512,871 € | 300,641 | 7.85% | 241,512,954 € | 301,891 | 7.87% |
| Maintenance | 1,046,384,255 € | 1,307,980 | 34.16% | 1,049,493,962 € | 1,311,867 | 34.21% |
| **TOTAL OPEX** | **1,286,897,125 €** | **1,608,621** | **42.01%** | **1,291,006,916 €** | **1,613,759** | **42.08%** |
| **TOTAL NON-DISC** | **3,063,160,290 €** | **3,828,950** | **100%** | **3,068,192,162 €** | **3,835,240** | **100%** |
| **TOTAL DISCOUNTTED** | **2,510,597,924 €** | **31,382,474** | **100%** | **2,514,342,349 €** | **31,429,279** | **100%** |

**Table 23. LCC main results for the two scenarios (Base and Yaw)**

These results indicate that the new technology represents around **€3.6 Million** of extra costs for the whole lifetime (discounted) of the wind farm, what means solely **0,13%** over the base case.

**Final note**. Additional information describing how the calculation have done are attached in annexes and in the Excel spreadsheet.

## 4.7 LCOE Calculations

### 4.7.1 LCOE Methodology

The levelized cost of energy (LCOE), that estimates the net present value of the unit cost of electricity produced over the lifetime of the Offshore Windfarm asset, can be calculated as

$$\frac{\sum_{t=0}^{Tfarm} \frac{LCCt}{(1+WACCreal)^t}}{\sum_{t=0}^{Tfarm} \frac{E}{(1+WACCreal)^t}} \quad \text{in €/MWh}$$

**Equation 1. LCOE formulation**

Where $T_{farm}$ is the lifetime duration of the wind farm (from construction to decommissioning) and E (MWh) is the total net energy produced.

In advance to the calculation, all the figures need to be adjusted for the inflation rate and the interest rate, in order to account for the time value of money considering that the service life of an Offshore Wind farm will be approximately 25 years. All costs were therefore discounted and inflated with the real discount rate ($WACC_{real}$) integrating the nominal cost of capital ($WACC_{nominal}$) with the inflation rate ($R_{inf}$ ), according to Fisher equation[11].

$$WACCreal = \frac{1 + WACC}{1 + Rinfl} - 1 \approx WACCnom - Rinfl$$

**Equation 2. WACC real calculation**

The WACC nominal is described by the formula:

$$WACCnom = \left(\frac{Eq}{V} * Re\right) + (\left(\frac{D}{V} * Rd\right) * (1 - T))$$

**Equation 3. WACC nominal**

Where:

Eq = market value of the firm's equity (market cap)
D = market value of the firm's debt
V = total value of capital (equity plus debt)
Eq/V = percentage of capital that is equity (30%)
D/V = percentage of capital that is debt (70%)
Re = cost of equity (required rate of return)
Rd = cost of debt (yield to maturity on existing debt)
T = tax rate, considered 25%

Being:

$$Re = Rf + \beta * (Rm - Rf)$$

Rf = the risk-free rate (typically the 10-year UE. Treasury bond yield)
β = equity beta (levered) representing the risk of the operation
Rm = annual return of the market

In the project, it was assumed that:

$R_{inf}$ was 1.5%
$WACC_{nominal}$ was 6.69%
$WACC_{real}$ around 5.19%

In relation to the Energy production, the following assumptions were taken:

| | | Yearly hours | 8,760 |
|---|---|---|---|
| **ENERGY PRODUCTION** | | **BASE** | **YAW** |
| **Gross Load Factor** | **%** | **80.38%** | **80.79%** |
| **Gross Energy Production** | **(MWh/MW/y)** | **7,041** | **7,077** |
| Wind Farm availability | % | 80.64% | 80.86% |
| **Net Energy production** | **(MWh/MW/y)** | **5,677.80** | **5,722.40** |
| **Net Load Factor** | **%** | **64.82%** | **65.32%** |
| WACC real | % | 5.19% | 5.19% |
| Inflation Rate | % | 2.00% | 2.00% |

**Table 24. Assumptions to calculate the differences in LCOE**

We assume a net capacity factor close to the most recent outstanding figures[12] (65% in Hywind Scotland project). The main results are the following:

| SCENARIOS/Concepts | Units | Base Fix | Base YAW |
|---|---|---|---|
| Total Present Value Costs | € | 2,510,597,924 | 2,514,342,349 |
| Total Energy Produced (Non discounted) | MWh | 113,556,000 | 114,448,000 |
| Total Energy Produced (Present Value) | MWh | 83,596,406 | 84,253,069 |
| Total incomes sales of energy (50€/MWh) | € | 4,179,820,290 | 4,212,653,426 |
| Average Cost (Present Value) per MW | €/MW | 3,138,247 | 3,142,928 |
| Total Net Energy Production (NPV) | MWh/MW | 104,496 | 105,316 |
| **LCOE** | €/MWh | 30.03 | 29.84 |
| Years | Nº | 25+1 | 25+1 |

**Table 25. Comparison of LCOE (from base and yaw scenarios )**

Selling price has been set in 50€/MWh. EDF has recently achieved this figure in Dunkerque[13] (northwest of France). The LCOE is improved with the new control system 0.196 €/MWh in absolute terms and 0.63% in relative terms.

Table 20 provides the gaining in absolute terms when you introduce the yaw control system

| MAIN CONCLUSIONS (YAW/BASE) | Unit | Absolute | Relative |
|---|---|---|---|
| Increase in LCC (Present Value) | € | -3,744,425 | -0.15% |
| Increase in Net Energy sales (Present Value) | € | 32,833,137 | 0.79% |
| Net differences | € | 29,088,712 | 1.16% |

**Table 26. Gaining in absolute and relative terms when applying the new control strategy**

**Around €29.1 Million is saved or 1,16% of total costs at present value.**

# 5 LIFE CYCLE ASSESMENT

## 5.1 Life cycle assessment definition

LCA is a method used to assess environmental aspects and potential environmental impacts throughout a wind power plant's life cycle from raw material acquisition through production, use, end-of-life treatment (reuse or recycling) and final disposal (i.e. cradle to grave)[14]

This comparative LCA will compare the environmental impact of the life cycle of an offshore wind power plant in relation to wake steering control. It will also compare the fraction of environmental impact each section of the life cycle contributes to the overall emissions of the wind turbines.

According to the ISO 14040/44 standards[15] [16] , an LCA study consists of four phases:

(1) goal and scope (framework and objective of the study).
(2) life cycle inventory (input/output analysis of mass and energy flows from operations along the product's value chain).
(3) life cycle impact assessment (evaluation of environmental relevance, e.g. global warming potential).
(4) interpretation (e.g. optimization potential) (ISO 14040: 2006, SIO 14044:2006).

## 5.2 Life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases

The life cycle inventory (LCI) stage qualitatively and quantitatively analyses the materials as well as the products and by-products generated, the environmental releases in terms of non-retained emissions to specified environmental compartments and the wastes to be treated (outputs) for the product system being studied. The LCI data can be used on its own to: understand total emissions, wastes and resource-use associated with the material or the product being studied; improve production or product performance; or be further analyzed and interpreted to provide insights into the potential environmental impacts from the system (life cycle impact assessment, LCIA and interpretation).

## 5.3 Goal

As mentioned, the goal of this study is to examine the potential environmental impacts associated with the production of electricity from 800 MW offshore wind power plant comprised of eighty DTU 10 MW RWT, two offshore substations and one onshore substation from a life cycle perspective (hereafter called "Baseline"). This environmental impact is then to be compared to a wake steering control (hereafter called "Yaw Control").

The impacts are to be evaluated using a set of conventional impact categories (e.g. GWP, AP, EP etc.).

## 5.4 Scope

This is a cradle to grave study, assessing the potential environmental impacts associated with electricity generated from 800 MW offshore wind power plant of DTU 10 MW RWT over its expected life cycle for 25 years.

This includes extraction of raw materials from the environment, manufacturing processes of components, production of the assembled wind turbines, logistics, use through to the point at which the product is disposed of and returned to the environment at end of life treatment recycling and final disposal. Figure 8 shows the system boundary for the offshore wind power plant system.

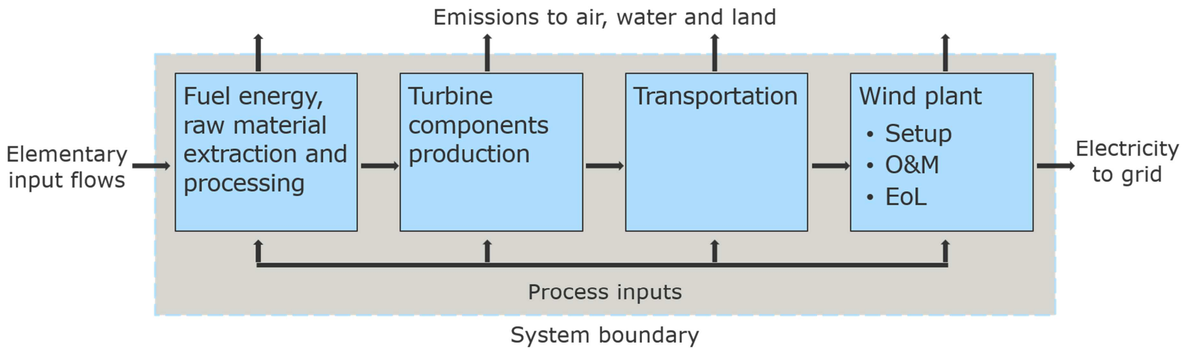



**Figure 8: Scope of LCA for 800 MW offshore wind power plant of DTU 10 MW RWT**

The following processes have been considered:

- Production of all parts of the wind power plant.
- Transportation of turbine components to wind power plant site.
- Site servicing and operations (including transport).
- Repair and replacement parts (due to wear and tear of moving parts within the lifetime of a wind turbine).
- Use phase power production including wind turbine availability (the capability of the turbine to operate when wind is blowing) and wake losses (arising from the decreased wind power generation capacity of wind a certain distance downwind of a turbine in its wake).
- End of life treatment of turbines.

### 5.4.1 Functional unit

The functional unit of this LCA study is total electricity production over 25 years plant lifetime which is 113,556 GWh for "Baseline" wind plant and 114,448 GWh for "Yaw control" wind plant[9].

### 5.4.2 System description

The offshore wind power plant itself account for the wind turbines, cabling and substation as shown in Figure 9. The boundaries of the offshore wind power plant are taken to be the point at which the power is delivered to the existing distribution grid.

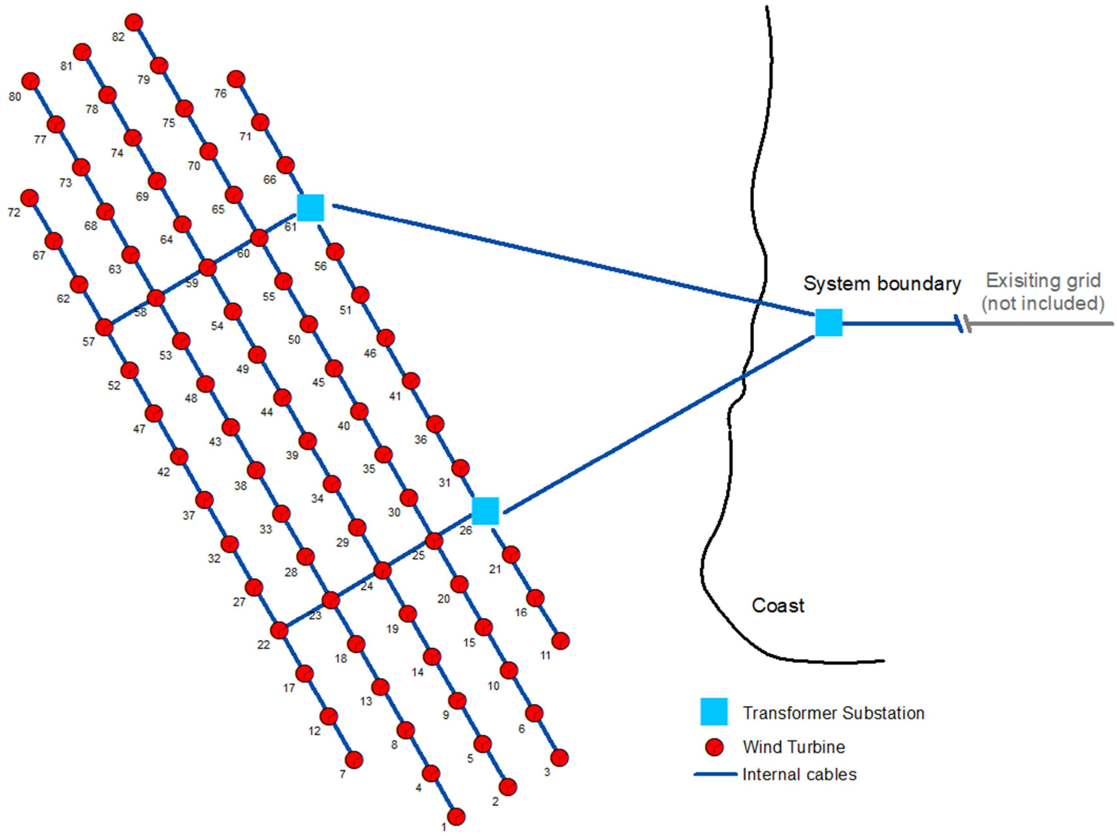



**Figure 9: Scope of the offshore power plant components**

The baseline information for the 10 MW DTU RWT has been collected from Project CL-Windcon Deliverable 1.1 and Project INNWIND Deliverable D1.21[17] and D4.34 for steel jacket structure[18]. The descriptions of the offshore wind turbine are listed in Table 21.

**Table 27: Baseline offshore wind power plant parameter**

| Description | Unit | Quantity |
|---|---|---|
| Wind speed | m/s | 11.4 |
| Mean water depth | m | 23 |
| No. of turbines | # | 80 |
| Wind regime | # | IEC Class 1A |
| Rotor orientation | # | clockwise, upwind |
| Control | # | variable speed, collective pitch |
| Turbine rating | MW | 10 |
| No. of blades | # | 3 |
| Rotor diameter | m | 178.3 |
| Hub height | m | 119 |
| Tower height | m | 25 |
| Maximum tip speed | m/s | 90 |
| Blade mass | kg | 41,700 |
| Hub mass | kg | 105,500 |

| Description | Unit | Quantity |
|---|---|---|
| Nacelle mass | kg | 446,036 |
| Tower mass | kg | 6,288,442 |
| Jacket foundation mass | kg | 1,866,000 |
| Distance btw. row | m | 1,426.4 |
| Distance btw. turbine | m | 1,248.1 |
| Distance to onshore substation | m | 80,000 |
| No. of substations | # | 2 |

### 5.4.3 Life cycle stages

The entire life cycle of an offshore wind power plant can be broken down into individual life cycle stages, as shown in Figure 10 used for this study.

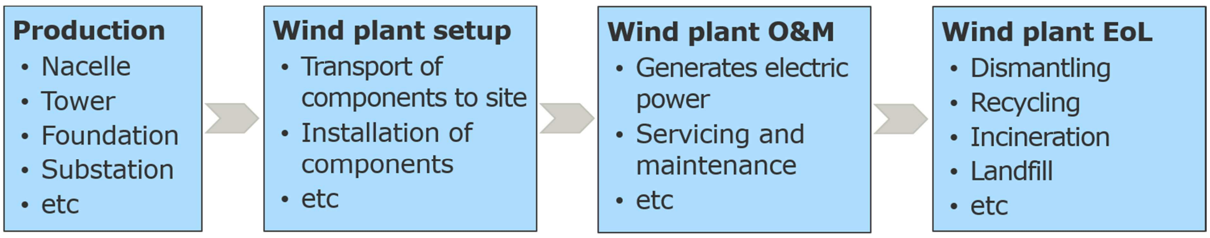



**Figure 10: Life cycle stages of a typical offshore wind power plant including typical activities**

*Production*; this includes production of raw materials and the manufacturing of wind power plant components such as the nacelle, rotor, towers, foundations, cables and substations. Transport of raw materials (e.g. steel, aluminum, copper, polymer etc.) to the specific production sites is not included within the scope of this study. As it is a theoretical/not real-constructed wind power plant, so no data available.

*Wind plant setup*; this begins with transporting components from manufacturing to construction site and erection of the wind power plant. Transport to construction site for installation of the wind power plant includes transport by truck and by transoceanic vessel.

*Wind plant operation and maintenance (O&M)*; this stage deals with the general running of the wind turbine plant as it generates electric power. Activities here include minor/major repairing and replacement of worn parts (e.g. the gearbox, power electrical system, etc.) over the lifetime of the wind plant. Transport to and from the turbines for operation and maintenance purposes is included in this stage.

Wind plant *end of life (EoL)*; at the end of its useful life the wind power plant components are dismantled. Final waste management of materials is also considered in this phase. Waste management options include recycling, incineration without energy recovery or by deposition in landfill sites.

### 5.4.4 Data collection / completeness

The data for the modeling of LCA have been taken from different sources i.e. expert estimations and published by a third party.

### 5.4.5 Cut-off criteria

Approximately 99% of the inputs and outputs of the entire life cycle has been accounted for. And none of the entries that fall outside the study had a higher relative contribution of 1%. These results have been scaled up 100% of the full mass of a wind farm with all its elements.

## 5.5 Assumptions

This section outlines the primary assumptions used in the LCA which affect the environmental performance of the wind power plant.

- Lifetime of Turbine is assumed to be 25 years.
- Because it is a theoretical/not real-constructed wind plant, therefore the source of data for the material inputs are adapted from many sources[2 17 8 1] and used in GaBi software with the professional database.
- Transportation of maintenance crew to and from the wind plant during servicing operations is based on the result of Project CL-Windcon Deliverable 4.5 (Walgern et al., 2019). During a yearly planned maintenance, only crew transfer vessel (CTV) is used while for corrective (unplanned) maintenance requires both CTV and jack-up vessel (JUV). See table below.

**Table 28: Vessel type requirement for corrective maintenance**

| Material | Minor repair | Major repair | Replacement |
|---|---|---|---|
| Gearbox | CTV | CTV | JUV |
| Generator | CTV | CTV | JUV |
| Main shaft | CTV | CTV | JUV |
| Power electrical system | CTV | CTV | CTV |
| Yaw system | CTV | CTV | JUV |
| Pitch system | CTV | CTV | JUV |
| Blades | CTV | CTV | JUV |

- Transport of raw materials to production sites have been excluded from this study and all components transport from production site to port is assumed to be 100 km by truck. A hub for loading all components to site is assumed to be 80 km.
- No marine vessel usage data during installation and dismantling was taken into consideration in setup and end of life stage respectively.
- The entire wind farm is collected at the end of life and each part of the turbine are treated as shown in Table 23.

**Table 29: End of life treatment for material used for a 10 MW DTU wind power plant[19]**

| Material | Treatment |
|---|---|
| Aluminium | 95% recycled + 5% landfilled |
| Cast iron | 95% recycled + 5% landfilled |
| Copper | 98% recycled + 2% landfilled |
| Lead | 98% recycled + 2% landfilled |
| Steel | 95% recycled + 5% landfilled |
| Reinforced plastic * | 30% landfilled + 70% incinerated |
| Lubricant | 100% incinerated |
| Polymer | 100% incinerated |
| Ceramic and concrete | 100% landfilled |

* Reinforced plastic includes glass fiber and plastic

## 5.6 Inventory analysis

This LCA study follows an attributional process-based approach, which focuses on quantifying the relevant environmental flows related to the wind power plant itself and describes the potential impacts of the power plant based on the physical material and energy flows.

GaBi software and its databases have been used to model the scenarios and generate the life cycle inventories and impact assessments on which the study conclusions are based.

## 5.7 Impact assessment categories and relevant metrics

The Life Cycle Inventory (LCI) data is then analyzed to assess and understand the product impact on the environment, which can be allocated in impact categories as following:

- Abiotic resource depletion (ADP elements)
- Abiotic resource depletion (ADP fossils)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Freshwater aquatic ecotoxicity potential (FAETP)
- Global warming potential (GWP)
- Human toxicity potential (HTP)
- Marine aquatic ecotoxicity potential (MAETP)
- Photochemical ozone creation potential (POCP)
- Terrestrial ecotoxicity potential (TETP)

These impact categories have reached international consensus and occur on different scales ranging from global impacts (GWP), to regional impacts (AP) and local impacts (POCP, EP and HTP)[20].

## 5.8 Scenario analyses

This deliverable presents the results of LCA from the reference wind power plant or "Baseline" and "Yaw control". The following tables show the varying set up of different parameters in scenario analyses:

**Table 30: Electricity production**

| Scenario | Per 25 years (GWh) |
|---|---|
| Baseline | 113,556 |
| Yaw control | 114,448 |

**Table 31: Total usage of vessel during corrective maintenance for the entire lifetime of the wind plant**

| Vessel | Times | Distance to shore |
|---|---|---|
| **Baseline** | | |
| CTV | 7,615 | |
| JUV | 2,462 | |
| **Yaw control** | | 80 km |
| CTV | 7,752 | |
| JUV | 2,583 | |

**Table 32: Number of corrective maintenances for key wind turbine components during the lifetime of wind power plant (Project CL-Windcon Deliverable 4.5)**

| Turbine component | Minor repair | Major repair | Replacement |
|---|---|---|---|
| **Baseline** | | | |
| Gearbox | 665.2 | 165.7 | 28.6 |
| Generator | 50.3 | 18.0 | 9.1 |
| Power electrical system | 387.9 | 44.3 | 1.8 |
| Yaw system | 413.9 | 20.0 | 8.6 |
| Pitch system | 270.9 | 37.8 | 12.9 |
| Blades | 203.1 | 46.9 | 43.7 |
| Main shaft | 240.6 | 28.3 | 8.8 |
| **Yaw control** | | | |
| Gearbox | 672.1 | 162.6 | 30.7 |
| Generator | 53.2 | 18.5 | 8.6 |
| Power electrical system | 382.9 | 46.8 | 1.8 |
| Yaw system | 410.4 | 21.2 | 8.3 |
| Pitch system | 272.0 | 37.7 | 11.5 |
| Blades | 210.2 | 48.5 | 43.4 |
| Main shaft | 250.1 | 27.9 | 9.5 |

## 5.9 Life Cycle assessment (LCA) model

The following model is created in the GaBi software. It represents a generic life cycle stages of 800 MW offshore wind power plant. An inputs-outputs breakdown of the custom-made processes is shown in Appendix A.

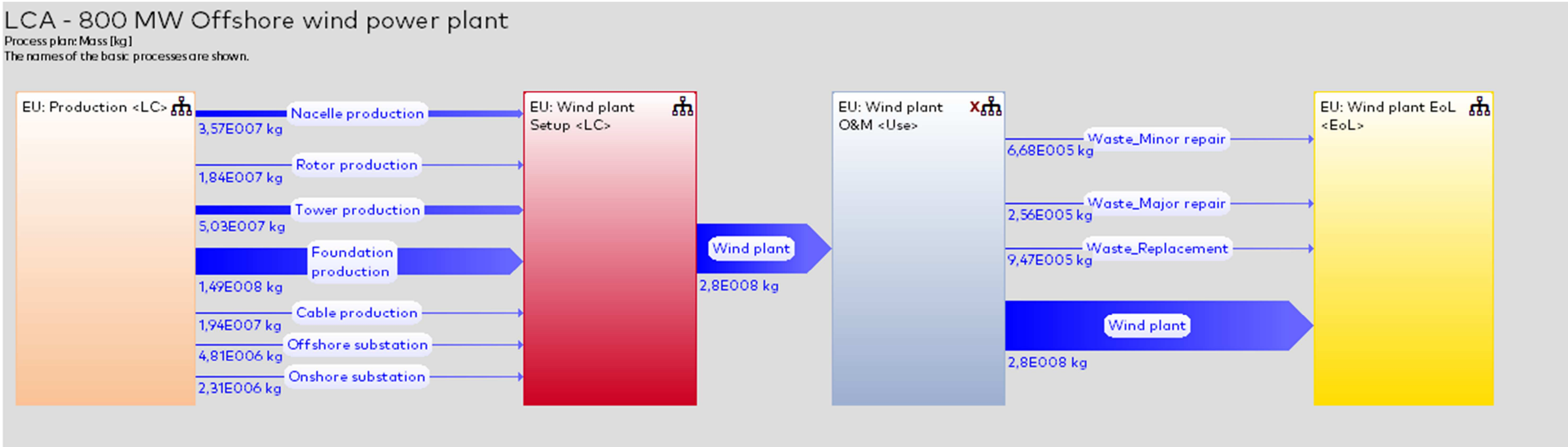



**Figure 11: Life cycle model of a 800 MW offshore wind power plant**

## 5.10 Materials inventory of DTU 10mw RWT offshore wind power plant

The materials inventory for the entire 800 MW offshore wind power plant of DTU 10 MW RWT is given in this section with an exception of the materials for maintenance servicing (replacement parts, major and minor repairs).

**Table 33: Material breakdown of 800 MW offshore wind power plant**

| Component | Unit | Material Classification | | | | | | | | | | Mass of Pcs. | Total Pcs. or Length | Total Mass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Aluminium | Cast iron | Ceramic | Concrete | Copper | Glass Fiber | Lead | Lubricant | Polymer | Steel | | | |
| **Nacelle** | | | | | | | | | | | | | | |
| Main Bearing | kg | | 4,028.7 | | | | | | | | 5,127.3 | 9,156 | 80 | 732,480 |
| Main Shaft | kg | | | | | | | | | | 45,042 | 45,042 | 80 | 3,603,360 |
| Gearbox | kg | 2,525.7 | 27,782.7 | | | 1,683.8 | | | | | 52,197.8 | 84,190 | 80 | 6,735,200 |
| Generator | kg | | 6,737.2 | | | 632.6 | | | 221.4 | 948.9 | 23,089.9 | 31,630 | 80 | 25,30,400 |
| Power electrical system | kg | 2,188.5 | 10,942.5 | | | 1459 | | | 726.7 | 1,823 | 19,335.3 | 36,475 | 80 | 2,918,000 |
| Yaw system | kg | 2,078 | 10,390 | | | 415.6 | | | | | 28,676.4 | 41,560 | 80 | 3,324,800 |
| Other parts | kg | 1,719.8 | 648.9 | | | 435 | | | 27.9 | 13,881.1 | 181,270.3 | 197,983 | 80 | 15,838,640 |
| **Rotor** | | | | | | | 125,100 | | | | | 125,100 | 80 | 10,008,000 |
| Blades | kg | | 43,314.63 | | | | 1,730.1 | | | | 25,640.27 | 70,685 | 80 | 5,654,800 |
| Hub | kg | 1,044.5 | | | | 696.3 | | | | | 33,074.2 | 34,815 | 80 | 2,785,200 |
| Pitch system | kg | | | | | | 125,100 | | | | | 125,100 | 80 | 10,008,000 |
| **Tower** | kg | 2,282.7 | | | | | | | | | 626,159.3 | 628,442 | 80 | 50,275,360 |
| **Foundation** | | | | | | | | | | | | | | |
| Jacket structure | kg | | | | | | | | | | 1,093,000 | 1,093,000 | 80 | 87,440,000 |
| Steel Appurtenances | kg | | | | | | | | | | 48,000 | 48,000 | 80 | 3,840,000 |
| Piles | kg | | | | | | | | | | 342,000 | 342,000 | 80 | 27,360,000 |
| Transition pieces | kg | | | | | | | | | | 258,000 | 258,000 | 80 | 20,640,000 |
| Grout | kg | | | | 125,000 | | | | | | | 125,000 | 80 | 10,000,000 |
| **Array cable (66 kV)** | | | | | | | | | | | | | (m) | |
| 95 mm² Cu-XLPE | kg/m | | | | | 2.64 | | 4.2 | | 3 | 11.76 | 21.6 | 240,000 | 5,184,000 |

| **Component** | **Unit** | **Material Classification** | | | | | | | | | | **Mass of Pcs.** | **Total Pcs. or Length** | **Total Mass** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Aluminium** | **Cast iron** | **Ceramic** | **Concrete** | **Copper** | **Glass Fiber** | **Lead** | **Lubricant** | **Polymer** | **Steel** | | | |
| 240 mm² Cu-XLPE | kg/m | | | | | 6.9 | | 6.3 | | 3.9 | 14.2 | 31.3 | 17,000 | 532,100 |
| 400 mm² Cu-XLPE | kg/m | | | | | 11.31 | | 7.62 | | 4.6 | 15.67 | 39.2 | 8,800 | 344,960 |
| 630 mm² Cu-XLPE | kg/m | | | | | 18.69 | | 10.41 | | 5.5 | 17.4 | 52 | 5,600 | 291,200 |
| **Export cable (220kV)** | | | | | | | | | | | | | (m) | |
| 1600 mm² Al-XLPE | kg/m | 9.12 | | | | | | 18.18 | | 13,08 | 44.72 | 85.1 | 149,000 | 12,679,900 |
| 2500 mm² Al-XLPE | kg/m | 4.89 | | | | | | 4.6 | | 2.54 | 5.57 | 17.6 | 18,000 | 316,800 |
| 2500 mm² Cu-XLPE | kg/m | | | | | 12.43 | | 7.41 | | 4.18 | 9.08 | 33.1 | 2,000 | 66,200 |
| **Offshore substation** | kg | 33,064 | 264,820 | | 125,000 | 97,675 | | | 121,760 | 7,510 | 1,754,480 | 2,404,309 | 2 | 4,808,618 |
| **Onshore substation** | kg | 264,112 | 963,600 | 90,000 | | 369,680 | | | 440,800 | 67,720 | 118,440 | 1,040,032 | 1 | 2,314,352 |

## 5.11 Impact assessment

### 5.11.1 Main results

Table 28 presents the total potential environmental impacts associated with 800 MW offshore wind power plant of DTU 10 MW RWT over the full lifetime cycle of 25 years.

**Table 34: Whole-life environmental impacts from 800 MW offshore wind power plant of DTU 10 MW RWT**

| Impact categories | Unit | Quantity |
|---|---|---|
| Abiotic Depletion (ADP elements) | kg Sb Equiv. | 8,209.082 |
| Acidification Potential (AP) | kg $SO_2$ Equiv. | 1,983,879.287 |
| Eutrophication Potential (EP) | kg $PO_4$ Equiv. | 183,935.453 |
| Freshwater Aquatic Ecotoxicity Pot. (FAETP) | kg DCB Equiv. | 1,081,540.39 |
| Global Warming Potential (GWP) | kg $CO_2$ Equiv. | 588,695,268.9 |
| Human Toxicity Potential (HTP) | kg DCB Equiv. | 110,437,910.7 |
| Marine Aquatic Ecotoxicity Pot. (MAETP) | kg DCB Equiv. | 49,678,076,260 |
| Photochem. Osidation Creation Potential (POCP) | kg Ethylene Equiv. | 220,323.443 |
| Terrestrial Ecotoxicity Potential (TETP) | kg DCB Equiv. | 948,633.74 |

Figure 12 presents the contribution of main components in the life cycle stages to each impact category (excluding end of life stage). In general, foundation has the most contribution to all environmental impact indicators between 24.5% to 52.5% except abiotic depletion elements, human toxicity potential, marine aquatic ecotoxicity potential and terrestrial ecotoxicity potential. The next most significant component is cable with contribution of 5.3% and 30.3%, except abiotic depletion elements where the contribution is 85.9%.

In all cases, the production stage has a contribution greater than 65% of the total impact and abiotic depletion elements, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential and terrestrial ecotoxicity potential by 93% to 99%. On the other hand, repairing and replacement of worn parts (O&M stage without marine vessel) has a significantly lower contribution and in the most cases less than 5% of total impact.

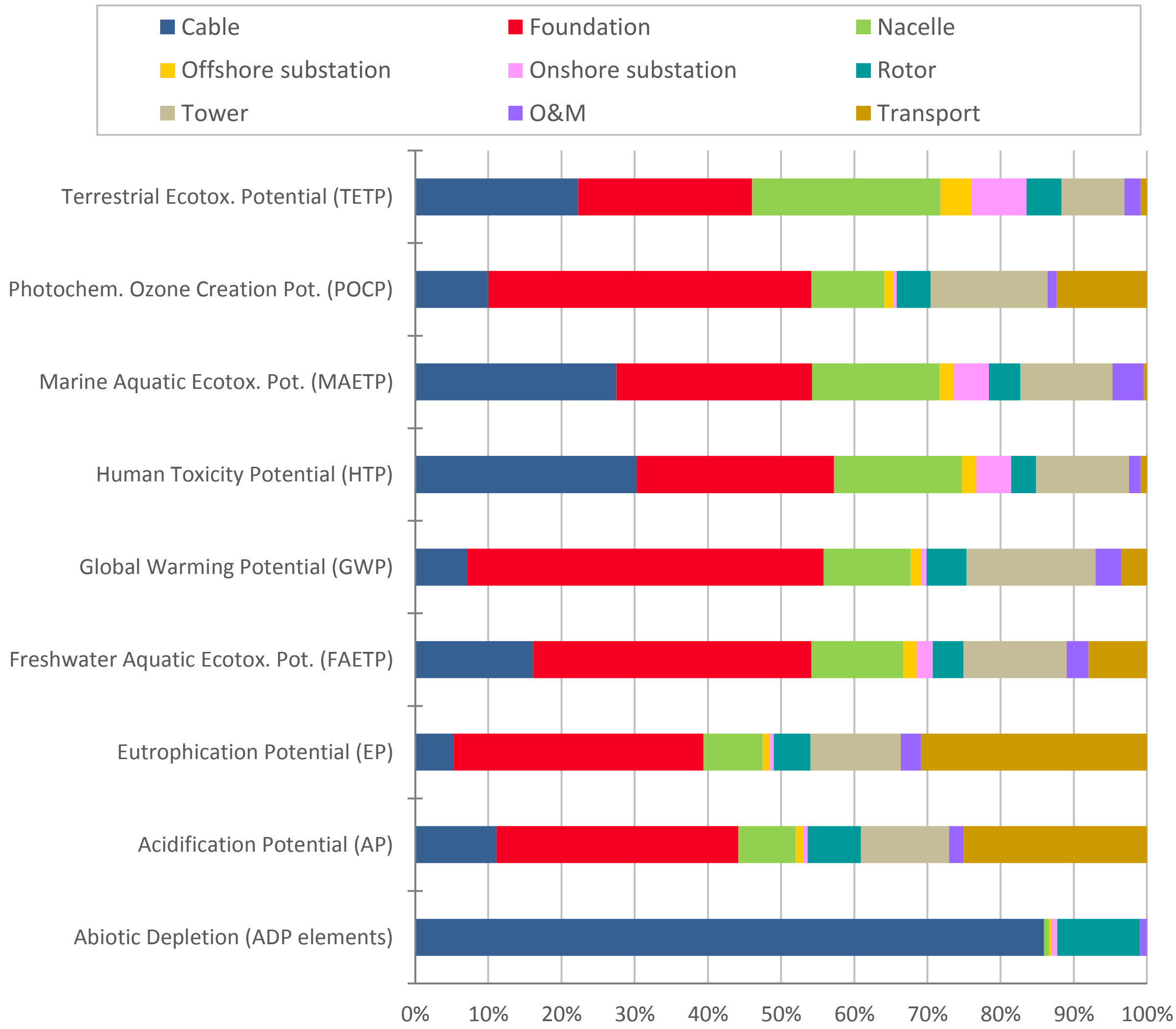



**Figure 12: Contribution of wind power plant main components to impact categories**

### 5.11.2 Analysis of results: impact categories

The results for each impact category are described in further detail in the following sections, identifying the potential impacts by life cycle stage of the wind power plant, and major contributing components and substances.

***Abiotic Depletion Potential (ADP elements)***

Abiotic depletion is commonly used as an indicator for depletion of non-living natural resources in the earth's crust, such as iron ores, aluminum or precious metals. It accounts for the ultimate geological reserves and the anticipated depletion rates. The mass of the element antimony (Sb) has been chosen as a metric for ADP, indicating the depletion of elements that were used in a life cycle of the power plant. The geographic scope of this indicator is at a global scale.

Figure 13 shows the abiotic depletion potential impact in the life cycle of wind power plant. The production stage clearly dominates the overall life cycle. This is primarily driven by the production of cable (86.7%) which is mainly relates to lead usage. The environmental credit at the end of life corresponds to the recycling of metals.

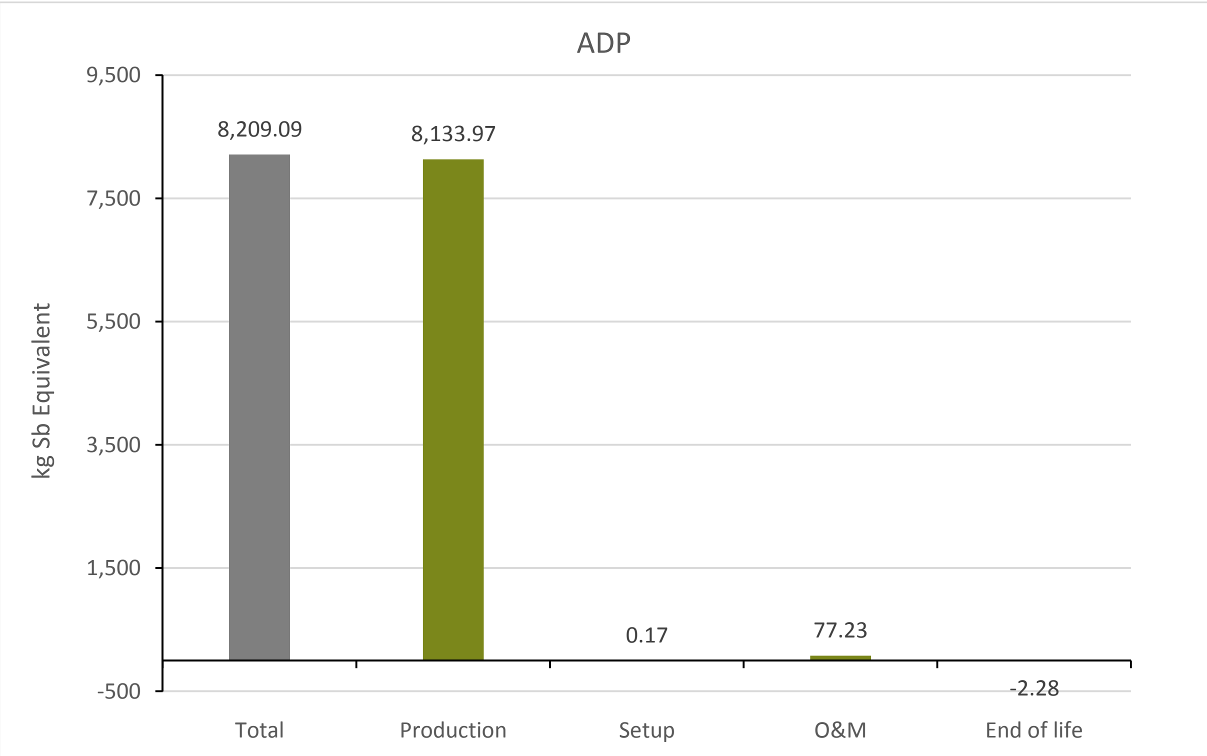



**Figure 13: Contribution in each life cycle stage of 800 MW offshore wind power plant to ADP**

***Acidification potential (AP)***

Acidification potential provides a measure of the decrease in the pH-value of rainwater and fog, which has the effect of acidifying pollutants on soil, groundwater, surface waters and ecosystems as well as on materials such as buildings. Acidification potential is generally a regional impact and is measured in mass of sulphur dioxide ($SO_2$) equivalents. The time span is eternity and the geographical scale varies between local scale and continental scale.

Figure 14 shows the acidification potential impact in the life cycle of wind power plant. The production and O&M stages affect this impact category with a contribution of 74.9% and 24.7% respectively. For the production stage, foundation has the highest share with 45.3% followed by, tower (16.5%), cable (15.2%), nacelle (10.8%) and Rotor (10%). For O&M stage, CTV vessel usage for minor repair has the most significantly contribution of 81.2%.

The end of life stage provides an environmental credit with -2.5% of this impact category, which relate to the avoidance of sulphur dioxide and nitrogen oxides emission to air.

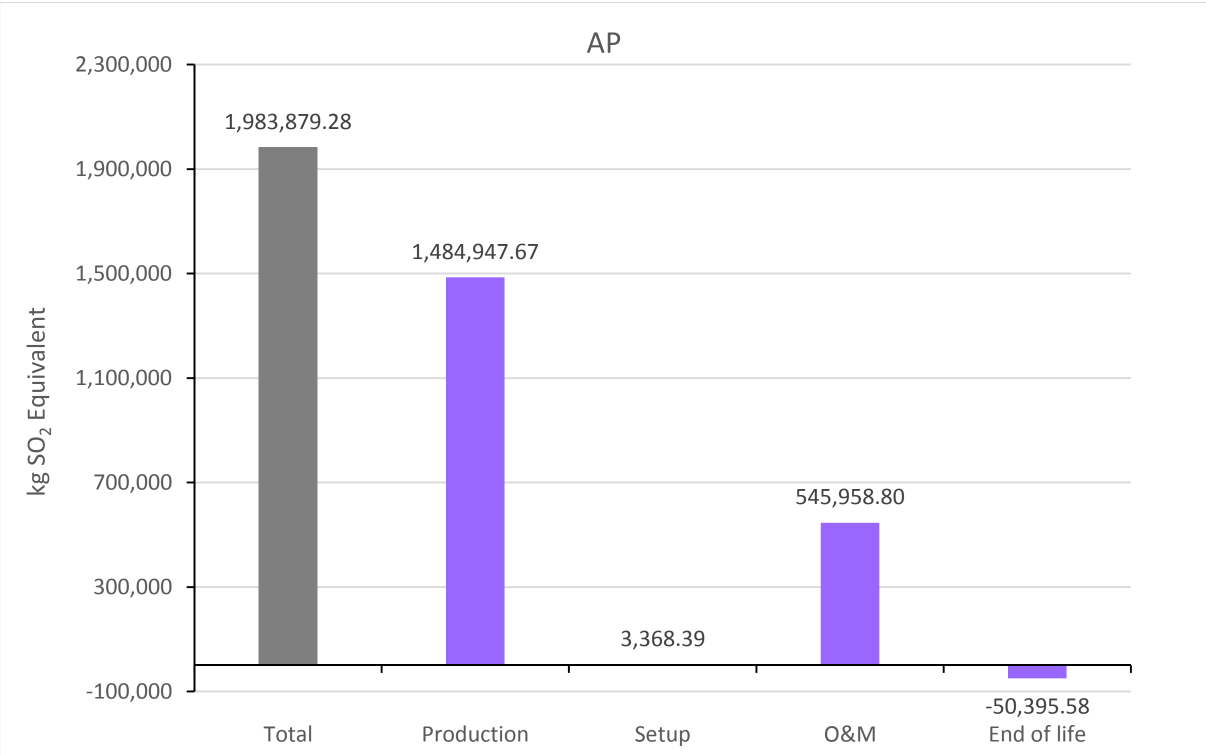



**Figure 14: Contribution in each life cycle stage of 800 MW offshore wind power plant to AP**

***Eutrophication potential (EP)***

Eutrophication describes the effects of over enrichment nutrient in aquatic or terrestrial environment. The mass of phosphate ($PO_4$) equivalent serves as a metric of this potential. Fate and exposure are not included, time span is eternity, and the geographical scale varies between local and continental scale.

Figure 15 shows eutrophication potential impact in the life cycle of wind power plant. Again, production and O&M stages account for the largest impacts with a contribution of 68.9% and 32% respectively. Within the production stage, foundation is the largest contributor to this impact category with a 47.7% share. Tower accounts for 17.2% while the production of cable contribute 14.7% to the total impacts. The end of life stage provides relatively lower credit with -0.7% in comparison to other impact indicators of this impact category. This is corresponding the avoidance of nitrogen oxides emission to air and heavy metal release to industrial soil.

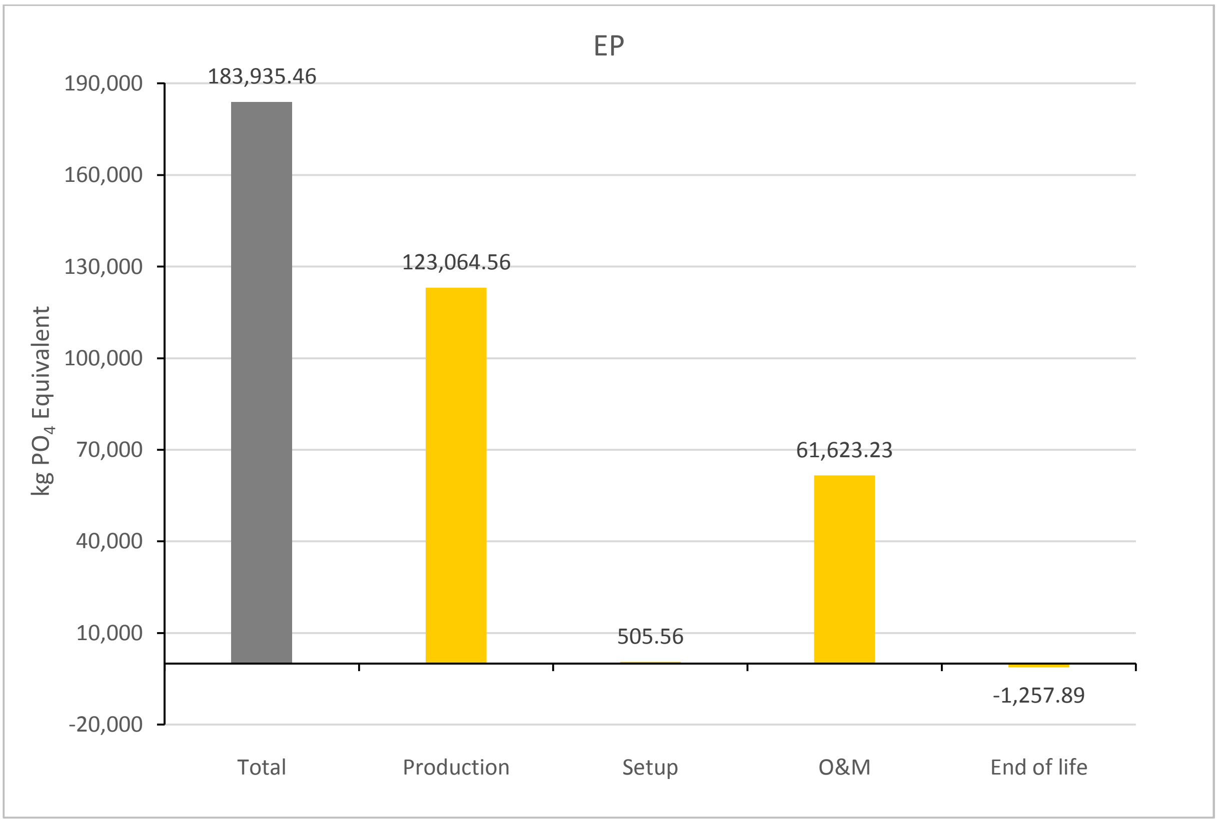



**Figure 15: Contribution in each life cycle stage of 800 MW offshore wind power plant to EP**

***Freshwater aquatic ecotoxicity potential (FAETP)***

The freshwater aquatic ecotoxicity potential refers to the potential for stressors to affect freshwater ecosystem, as a result of emissions of toxic substance to air, water and soil, and is measured in mass of dichlorobenzene equivalents. The geographic scope of this indicator applies at global, continental, regional and local scale.

Figure 16 presents freshwater aquatic ecotoxicity potential impact in the life cycle of wind power plant. Production stage of the power plant plays a key role in this impact category, which mainly relates to the production of foundation (42.7%), cable (18.1%), tower (15.8%), and the nacelle (14.1%) respectively. The environmental credit at the end of life for this impact relates to steel recycling which avoids production of this material.

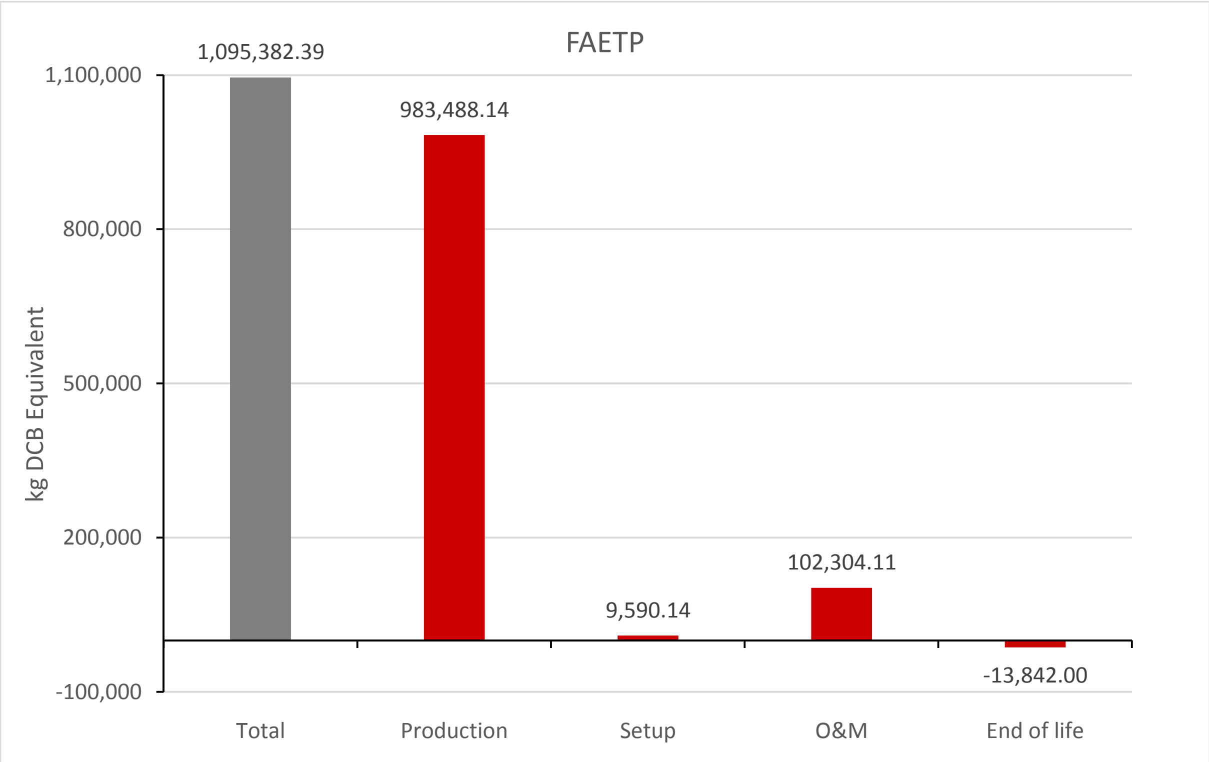



**Figure 16: Contribution in each life cycle stage of 800 MW offshore wind power plant to FAETP**

***Global warming potential (GWP)***

In general, global warming potential is used to evaluate the climate change due to the release of greenhouse gases into the atmosphere. This potential is assessed for a time of 100 years and referenced to equivalents of carbon dioxide. The geographic scope of this indicator is at global scale.

Figure 17 presents the global warming potential impact in the life cycle of wind power plant. Like in other impact categories. the production stage has the largest impact contribution of 91.9% and followed by O&M stage with a contribution of 6.4%. The production of foundation (52.5%), tower (18.9%), nacelle (12.8%), cable (7.6%) and rotor (5.9%) are the primary components contributing to this impact. Over the life cycle, the major contributing substances to global warming potential are the emissions to air of carbon dioxide (97.2%), methane (2.2%) and nitrous oxide (0.2%).

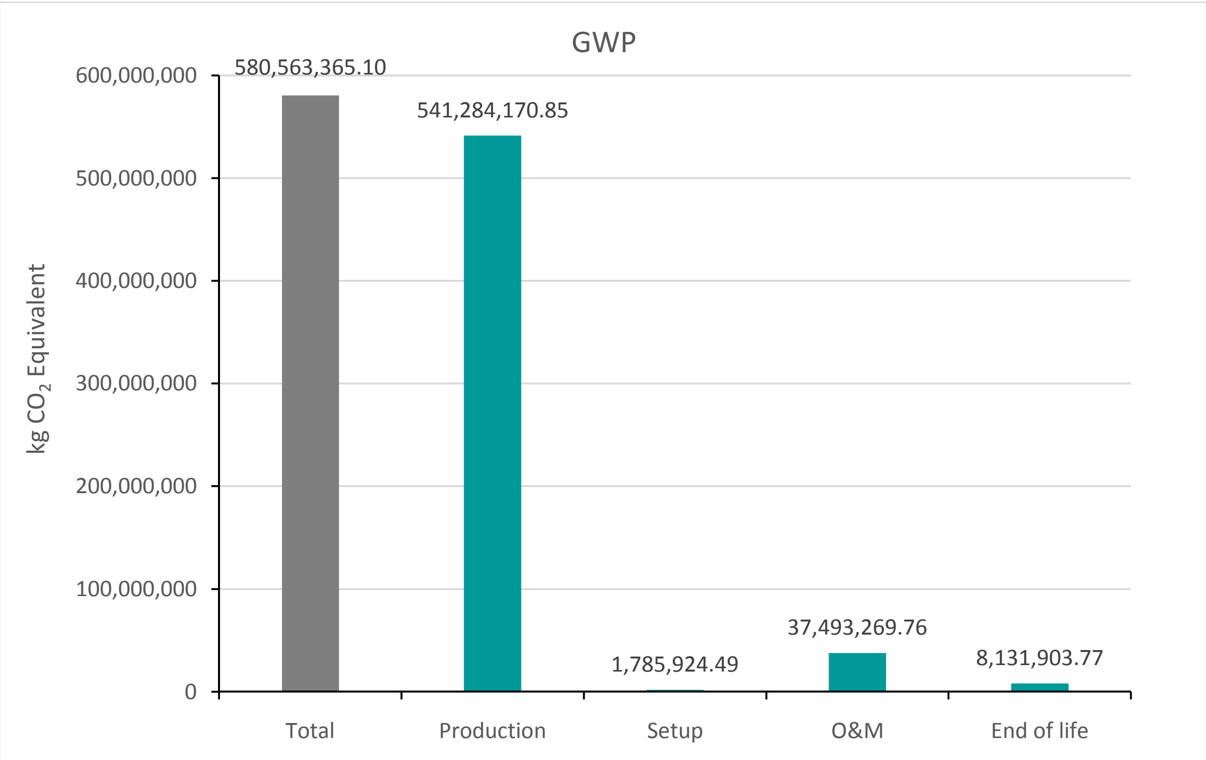



**Figure 17: Contribution in each life cycle stage of 800 MW offshore wind power plant to GWP**

***Human toxicity potential (HTP)***

Human toxicity potential impacts result on human health, due to emission of several substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents. Health risks of exposure in the working environment are not included. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.

Figure 18 presents the human toxicity potential impact in the life cycle of wind power plant. The production stage dominates the life cycle impacts, with the production of cable (30.3%), foundation (27%), nacelle (17.5%) and tower (12.7%). The main contributing flows are the release of VOCs (85.3%), heavy metals (10%) and inorganic substances (4.5%) to air. The end of life stage provides relatively low environmental credit with -1% of this impact category.

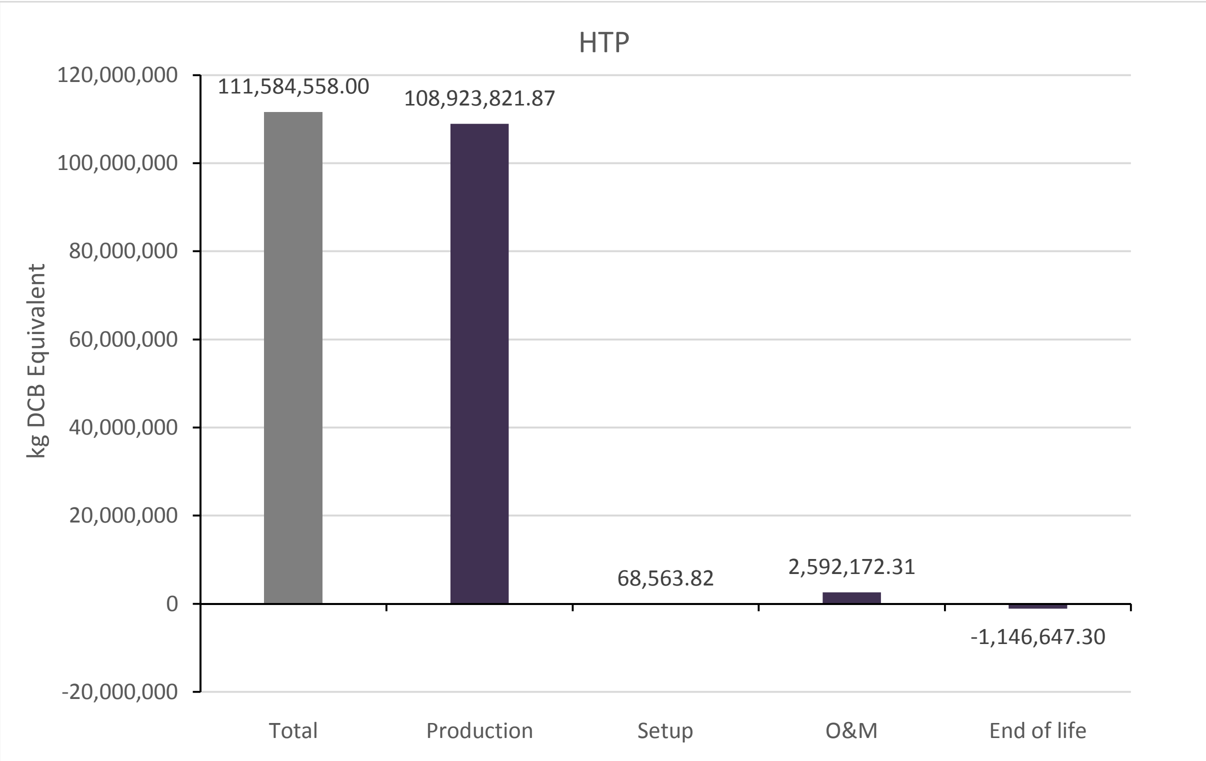



**Figure 18: Contribution in each life cycle stage of 800 MW offshore wind power plant to HTP**

***Marine aquatic ecotoxicity potential (MAETP)***

During the life cycle stage of the power plant, several toxic substances in soil, water and air may have an impact on marine water ecosystem. The MAETP describes these impacts and is measured in mass of dichlorobenzene equivalents. The geographic scope of this indicator applies at global, continental, regional and local scale.

Figure 19 shows the marine aquatic ecotoxicity potential impact in the life cycle of wind power plant. Like other impact categories, it is production accounts for the largest impacts. For the production stage, the production of cable is the largest contributor to this impact category with a 28.9% share. Foundation accounts for 28.1% while nacelle contributes 18.3% to the total impacts. The end of life stage offers substantial environmental credit (-13.9%), which is mainly associated with the avoided emission of hydrogen fluoride to air (98%) from the recycling of aluminum and steel.

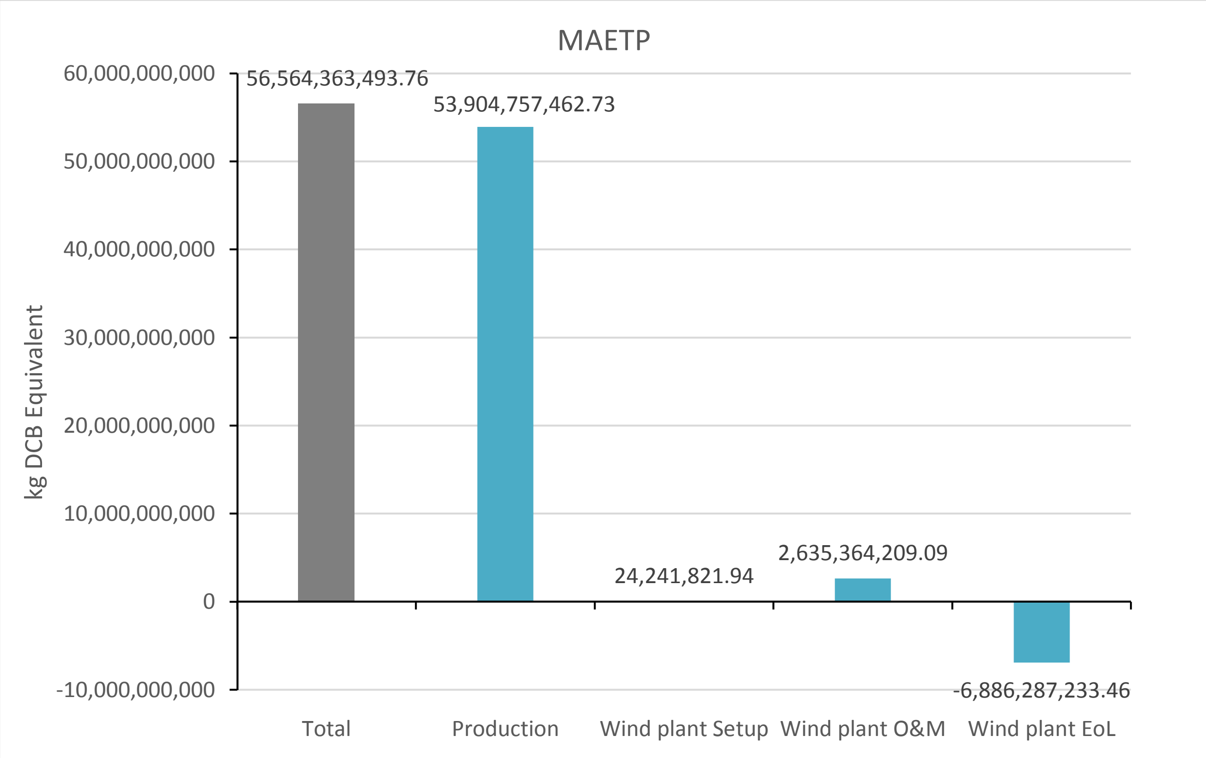



**Figure 19: Contribution in each life cycle stage of 800 MW offshore wind power plant to MAETP**

***Photochemical oxidant creation potential (POCP)***

Photochemical oxidant creation is the formation of ozone and other oxidizing compounds from primary pollutants which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with summer smog. The POCP describes these impacts and is measured in mass of ethylene equivalents. The time span is 5 days and the geographical scale varies between local and continental scale.

Figure 20 shows the photochemical oxidant creation potential impact in the life cycle of wind power plant. The production stage accounts for the largest impacts, which is primarily related to the production of foundation (51.1%), tower (18.5%), cable (11.6%), nacelle (11.5%) and rotor (5.3%). The main contributing substances are carbon monoxide (58.8%), sulphur dioxide (21.7%), nitrogen oxides (11.6%), non-methane volatile organic compounds (5.3%) and methane (1.3%) from the production of metals and glass fiber. End of life provides a credit of -1.2% of the potential impact.

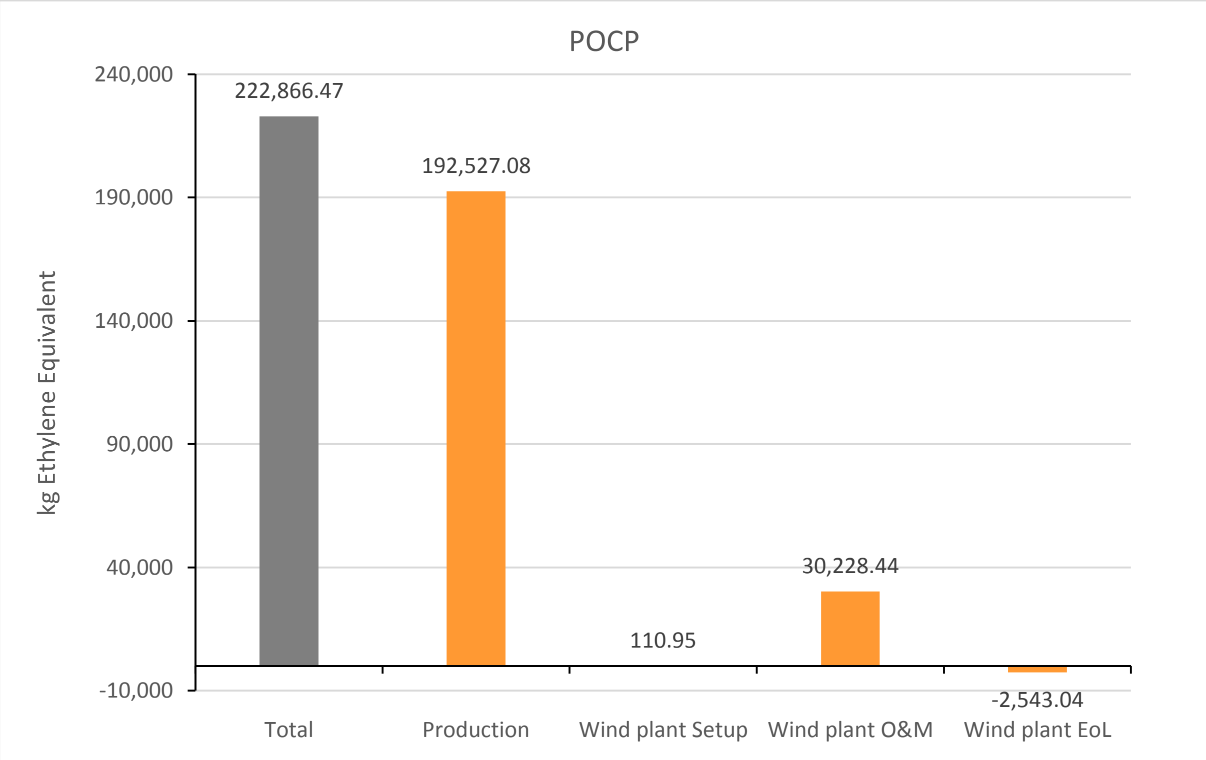



**Figure 20: Contribution in each life cycle stage of 800 MW offshore wind power plant to POCP**

***Terrestrial ecotoxicity potential (TETP)***

Terrestrial ecotoxicity refers to the impact on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents. The geographic scope of this indicator applies at global, continental, regional and local scale.

Figure 21 shows the terrestrial ecotoxicity potential impact in the life cycle of wind power plant. The results reveal that the production stage dominates the life cycle with 96.6% share, which is related to the emission of heavy metal to air as well as heavy metal releases to industrial soil with a contribution of 64% and 34.4% respectively. Chromium, mercury vanadium and arsenic are the main contributing heavy metal.

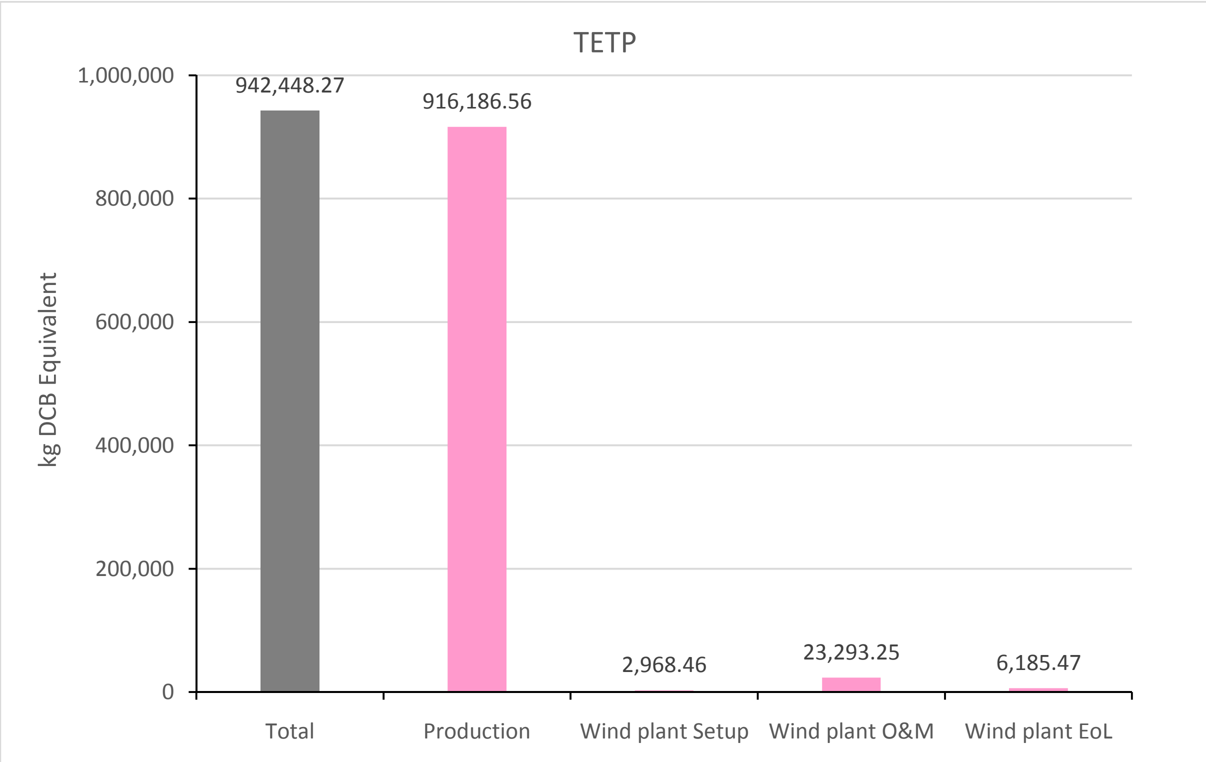



**Figure 21: Contribution in each life cycle stage of 800 MW offshore wind power plant to TETP**

## 5.12 Comparative scenario impact assessment results

For the purpose of a comparison between "Baseline" plant and "Yaw control", the obtained environmental potential impacts are normalized to the total electricity production per kWh from the wind power plant over the 25-year time frame. As mentioned previously in scenario analyses section, the total electricity production of baseline plant is 113,556 GWh and yaw control is 114,448 GWh over the wind plant lifetime.

In general, the result in Figure 22 shows that "Yaw control" scenario case causes less environmental impacts than "Baseline" case around 0.38% to 0.76%, except acidification potential and eutrophication potential. For the carbon footprint, the "Yaw control" reduce the emission of carbon dioxide about 35 mg$CO_2$-eq per kWh of electricity production from the baseline wind power plant which is equivalent to eliminate 107 cars from road (driving 10.000 km/year) every year.

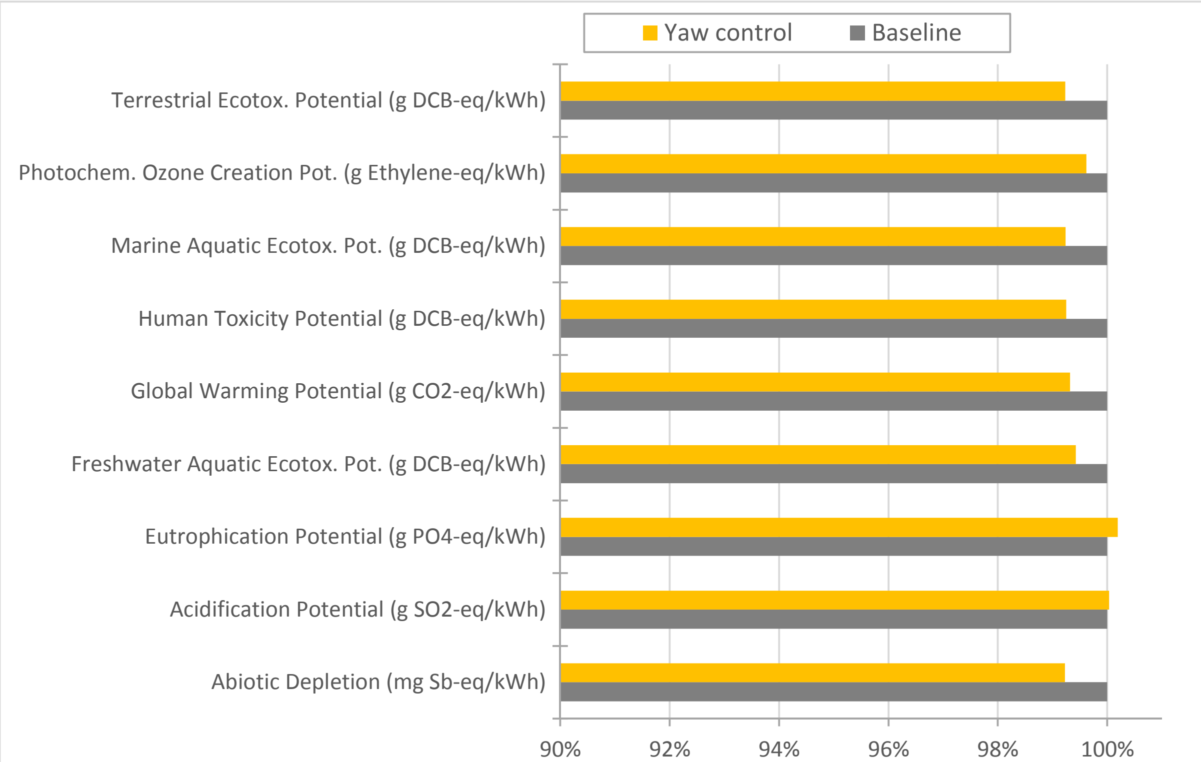



**Figure 22: Whole-life environmental impacts of scenario wind power plant (unit shown in g or mg per kWh)**

## 5.13 Interpretation

According to the life cycle impact assessment in this chapter and the life cycle inventory data, which is presented in Appendix B, the production stage of the life cycle is the largest contributor for all potential environmental impacts which is mainly related to the production of foundation. But the production of cable is the most contributor in abiotic depletion potential. From the comparative scenario assessment, it is clear that the "Yaw control" wind plant case reduce the potential environmental effect for all impact categories except acidification potential and eutrophication potential, when normalized to 1 kWh of electricity production. The higher impact in "Yaw control" is reflected the high demand of using marine vessel during the maintenance service.

# 6 LIFETIME EXTENSION ANALYSIS

## 6.1 Introduction to Lifetime Extension

After the LCC and LCA analysis, we will like to add here a theoretical exercise to verify if the lifetime of the components of the non-controlled wind turbine changes if wake steering control is introduced. Results are not considered in the previous calculations, but the potential scenarios will be included as variations in the sensibility analysis to be submitted in D5.2 entitled “Feasibility analysis and Business models”. Without anticipating the results of this study, it is important to stress that the analysis is based on load calculations performed with the aero-elastic simulation module LACFLEX for a specific wind farm set up and environmental conditions and does not pursues the goal to generalise the results for the wake steering controller type.

Lifetime extension addresses the topic if at the end of its calculated lifetime an asset possesses the structural health to continue operation for some time longer. The assessment of a potential lifetime extension can be done by two methods; through renewed calculation (analytical) or through inspection (practical). The analytical method compares the expected design lifetime calculated with the design loads and the actual specific site loads experienced by the asset. These come from monitoring systems and weather data collected throughout the lifetime and can be lower than the design loads. The discrepancy is then calculated into the remaining useful lifetime (RUL) of the wind turbine.

This study aims to calculate the RUL of the Norcowe wind farm[21] in the case of an active wake steering controller. The non-controller baseline case will serve as reference case scenario of which the damage at the end of a 25-year-lifetime will be compared to the lifetime damage equivalent load (DEL) of the controller case.

## 6.2 Methodology

The potential of remaining lifetime was studied on one exemplary wind turbine (turbine 4) of the Norcowe wind farm. This turbine will be for some directions in free stream, and for others in a single wake (from WTG 1, 2, 3, 7), and multiple wake (from the WTGs (6, 5), (21, 15, 9), or (80, 77, …, 13, 8). This way the turbine will be under different wake conditions throughout the lifetime. The single wake will be at different distances between the turbines and the multiple wake will be for different distances and a changing number of turbines.

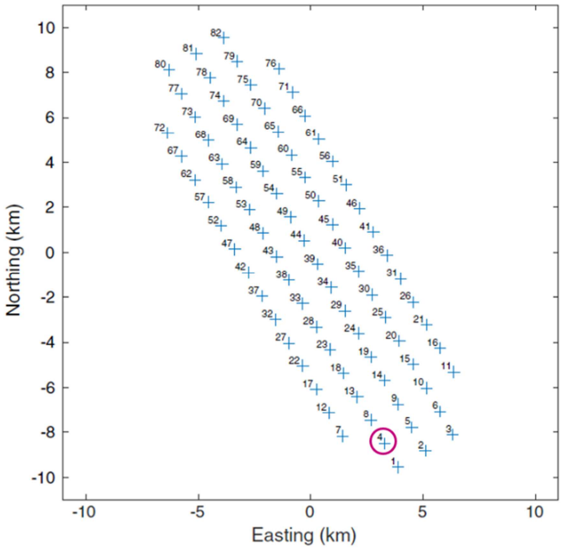



**Figure 23: Norcowe wind farm layout, (Bak, et al., 2017). Studied turbine with circle.**

The procedure of the calculation of the lifetime DEL for the 10MW wind turbine is presented in a flow chart given in Figure 23: Norcowe wind farm layout, . Studied turbine with circle.

In a first step, a look-up table containing the damage equivalent loads (DEL) from chosen sensors under a range of wind/wave and yaw conditions has been used. The studied sensors are listed in Table 35 and the corresponding coordinate systems are illustrated in Figure 25: Sensor coordinate systems The LACFLEX software with which the DEL look-up table was built, can only simulate the loads in the hub. Therefore, the assumption was made to link the fatigue of the shaft to the hub loads. Additionally, the lifetime analysis was also performed for the rotor blades. This way the two components for which D4.5[9] has linked a change in DEL to a change in failure rates have been studied in this lifetime assessment. To account for the sea states in the load calculations the most probable significant wave height $H_S$ and peak period $T_P$, according to the Fino3 met mast data, were assigned to every wind speed at hub height $V_w$ between 4 m/s and 25 m/s. The respective wave parameters are listed in Table 36: Corresponding wind/wave conditions used for the calculation of the DEL look-up table.

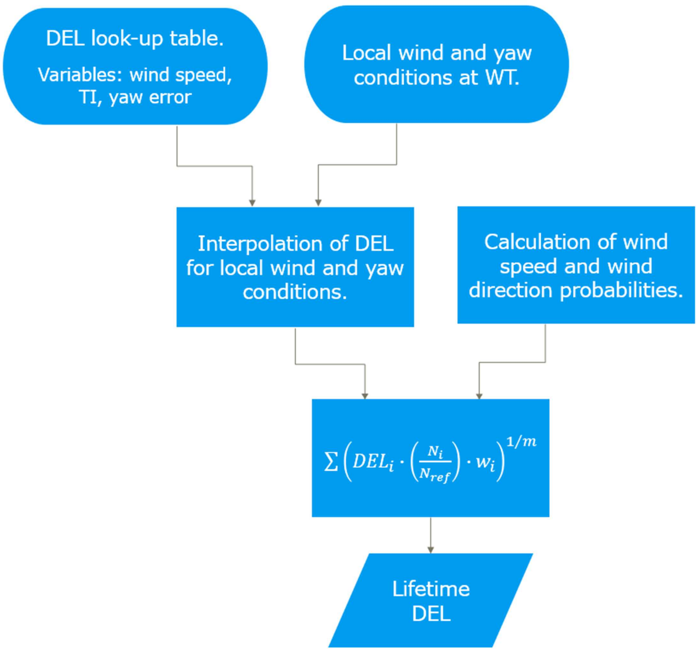
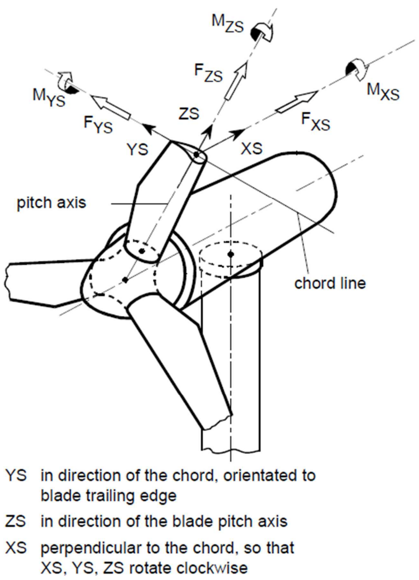



**Figure 24: Methodology for the calculation the Lifetime DEL.**

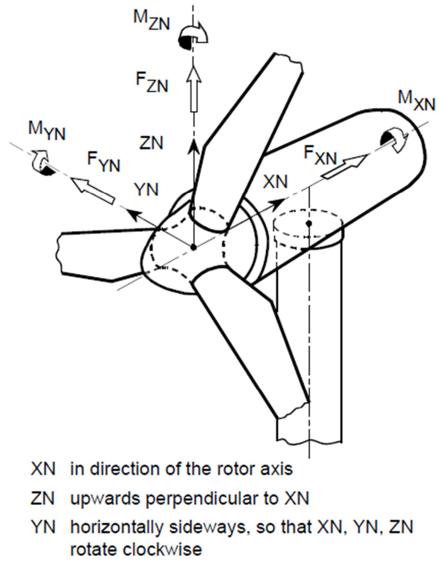
Turbulence intensities between 0.05 and 0.4 with steps of 0.05 were combined with wind speeds between 4 m/s and 25 m/s with steps of 1m/s. Additionally, the yaw error was varied between -30 degrees and +30 degrees with a step of 5 degrees. These different parameters have all been combined with each other to form a vast amount of load cases. For each of these cases the DEL has been calculated from a 10 min time series with 3 wind seeds and stored in a SQL database.

| Component | Sensor | Name | Reference system |
|---|---|---|---|
| **Blade** | $M_{XS1,2,3}$ | Blade root edgewise | Chord coordinate system |
| | $M_{YS1,2,3}$ | Blade root flapwise | Chord coordinate system |
| | $M_{ZS1,2,3}$ | | Chord coordinate system |
| **Hub** | $M_{XN}$ | | Hub coordinate system |
| | $M_{YN}$ | Nodding moment | Hub coordinate system (non-rotating) |
| | $M_{ZN}$ | Yawing moment | Hub coordinate system (non-rotating) |
| | $M_{XR}$ | | Rotor coordinate system (non-rotating) |
| | $M_{YR}$ | Nodding moment | Rotor coordinate system (rotating) |
| | $M_{ZR}$ | Yawing moment | Rotor coordinate system (rotating) |

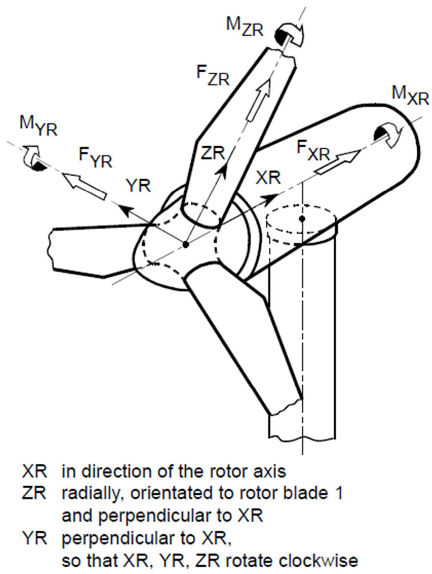
**Table 35: List of sensors assessed for lifetime extension**




Chord coordinate system




Hub coordinate system




Rotor coordinate system

**Figure 25: Sensor coordinate systems (GL 2010)**

| $V_w$ [m/s] | $H_S$ [m] | $T_P$ [s] |
|---|---|---|
| **4** | 0.5 | 6 |
| **5** | 0.5 | 6 |
| **6** | 1 | 6 |
| **7** | 1 | 6 |
| **8** | 1 | 6 |
| **9** | 1 | 6 |
| **10** | 1.5 | 6 |
| **11** | 1.5 | 6 |
| **12** | 2 | 6 |
| **13** | 2 | 6.5 |
| **14** | 2.5 | 7 |

| $V_w$ [m/s] | $H_S$ [m] | $T_P$ [s] |
|---|---|---|
| **15** | 2.5 | 7.5 |
| **16** | 3 | 8 |
| **17** | 3 | 8 |
| **18** | 3.5 | 8 |
| **19** | 3.5 | 8.5 |
| **20** | 4 | 9.5 |
| **21** | 4.5 | 10 |
| **22** | 5 | 10.5 |
| **23** | 5 | 10.5 |
| **24** | 5.5 | 11 |
| **25** | 6 | 11 |

**Table 36: Corresponding wind/wave conditions used for the calculation of the DEL look-up table.**

In a next step, the local wind speeds and turbulence intensities, as well as, the yaw settings for all ambient wind speed and wind direction combinations were extracted from the wake steering optimization results from ECN. These local wind and yaw conditions have been taken for the reference wind turbine 4 for the controller and non-controller case.

From the Norcowe reference wind farm met ocean data, which come from the Fino3 met mast, the occurrence probabilities of the wind speed and wind direction were calculated and assigned to each of the local wind conditions of the turbine.

These parameters, combined in a table, serve as input to interpolate the individual DELs ($DEL_i$) for every load condition from the DEL look-up table. With the assigned probability these $DEL_i$ are combined to a total DEL over the lifetime ($DEL_{Lifetime}$) of the wind turbine, as shown in equation (Equation 4). The weighting factor $w_i$ is used to weight the different damages considering the occurrence probability of their associated load conditions. The Wöhler coefficient $m$ describes the material behaviour and is described in subchapter 6.2.1. $N_i$ is the number of load cycles of the individual DEL and $N_{ref}$ is the number of load cycles for the entire 25-year lifetime. It is assumed to be equal to $10^7$ load cycles.

$$\boldsymbol{DEL_{Lifetime}} = \sum \left( \boldsymbol{DEL_i} \cdot \left( \frac{\boldsymbol{N_i}}{\boldsymbol{N_{ref}}} \right) \cdot \boldsymbol{w_i} \right)^{\boldsymbol{1/m}} \qquad \text{(Equation 4)}$$

The non-controller case is taken as the baseline case which is laid out for a lifetime of 25 years and to which the yaw-controller case is compared. For the yaw-controller and the nominal baseline case the lifetime DELs ($DEL_{YAW\ Lifetime}$ and $DEL_{NOM\ Lifetime}$) are calculated for the different sensors from Table 35. The RUL, which can also be a negative number, in case of an increase in loads, is calculated with the following equation. $a_{Lifetime}$ is the design lifetime of the wind turbine of 25 years and m being the Wöhler coefficient.

$$RUL = \frac{a_{Lifetime}}{\left(\frac{DEL_{YAW\ Lifetime}}{DEL_{NOM\ Lifetime}}\right)^m} - a_{Lifetime} \quad \text{(Equation 5)}$$

### 6.2.1 S-N curves

Material stresses leading to fatigue appear in cycles. The number of stress cycles and the amplitude of the stress are the decisive factors leading to material failure. Material fatigue properties are often described using S-N curves (Wöhler curve). They show the relation between the stress amplitude ranges and the number of cycles leading to failure for stresses within this range. The gradient of a material's S-N curve is described by the parameter $m$, the Wöhler coefficient. For the calculation of the DEL look-up table and the lifetime DEL, Wöhler coefficients of 4 and 10 are used[9]. The blades which are composite materials use $m = 10$ and are the most fragile component of the wind turbine. The other steel components use $m = 4$.

## 6.3 Results

The remaining useful lifetime has been calculated for the sensors of the blades and the hub. The results are summarized in **Table 37** and indicate increase or decrease of the lifetime of wind turbine 4 due to the impact of the yaw controller.

| Blades | $M_{XS1}$ | $M_{XS2}$ | $M_{XS3}$ | $M_{YS1}$ | $M_{YS2}$ | $M_{YS3}$ | $M_{ZS1}$ | $M_{ZS2}$ | $M_{ZS3}$ |
|---|---|---|---|---|---|---|---|---|---|
| | -0.14 | 0.08 | -0.11 | -0.11 | -0.01 | -0.11 | -0.13 | -0.02 | -0.10 |
| **Hub** | $M_{XN}$ | $M_{YN}$ | $M_{ZN}$ | $M_{XR}$ | $M_{YR}$ | $M_{ZR}$ | | | |
| | 1.84 | 0.74 | 0.83 | 1.84 | -1.51 | -1.44 | | | |

**Table 37: Remaining Useful Lifetime (RUL) of the 10 MW reference WT in years.**

## 6.4 Interpretation

The results show mainly a decrease of the remaining useful lifetime of the different sensors which is due to the general increase of fatigue loads in the controller case within the NORCOWE reference wind farm documented in D4.5 (CL-Windcon Deliverable D4.5, 2019)[9].

The blades show small reductions of the lifetime of a maximum 0.14 years which equals to less than two months. Other blades show even smaller lifetime reductions due to the fatigue loads and the remaining lifetime becomes even positive in one case.

The hub loads show different results for the rotating and non-rotating coordinate system. The non-rotating system reaches a lifetime gain of almost 2 years whereas the rotating system shows a decrease of lifetime of 1.5 years for the controller case. MxN/R turns around the rotation axis of the hub and measures the same forces in both cases and therefore shows equal values for the rotating and non-rotating system.

The differences occur for the Mx and My moments and are caused by the rotor plane which is turned out of the wind direction for the yaw case. The wind conditions in which the yaw controller is activated have an occurrence probability of approximately 33% of the lifetime. This is significantly high and has an impact on the loads in the controller case. The rotor plane experiences a cross wind component for which in one half of the rotor plane the blade needs to go against that wind and for the other half it goes with the wind. This alternating loading and unloading are transferred to the hub and presents additional load cycles which are reflected in the results of the rotating coordinate system. The turbulences in the wind also have a stronger effect on the loads when the turbines are inclined than when the yaw error is 0°.

The hub loads show for the non-rotating moments an increase of the lifetime of almost 2 years due to a small decrease in the loads for the controller case. The sensors MyN and MzN in the non-rotating coordinate system do not change their position with the rotation of the blades and do not reflect the load alternation of the rotating blades. However, they show the static effect of the cross wind. The orthogonal component of the cross wind is smaller in comparison to the front wind of the baseline case and therefore influences the moments MyN and MzN in a positive way (for the yawed position).

The lifetime extension of the system is measured by its weakest part which is the MyR moment of the hub and presents a decrease of the turbine lifetime 1.5 years. This means that this sensor reaches the calculated design lifetime 1.5 years earlier than in the non-controller case. As D4.5 predicted an increase of the failure rate for the main shaft this statement is congruent with the presented results. It is assumed that the increased maintenance activity in the controller case for the affected components can balance this loss in component lifetime.

# 7 CONCLUSIONS

CL-WINDCON has developed advanced control algorithms for axial induction and wake redirection that optimize the operation of the wind farm for a balance between annual energy production, life, and O&M cost, aimed at minimizing lifetime LCoE. To this end, it has applied techniques including loads-optimized power curtailment, event triggered Individual Pitch Control (IPC) for loads reduction under partial wake conditions, fault-tolerant and fast wake recovery techniques. CL-WINDCON has taken farm-level controls from the current non-existing or simplistic static approach, to dynamic open and closed-loop control strategies with the aim to improve the efficiency, O&M costs and LCoE.

The study carried out in the deliverable D4.6 intends to compare a wind farm without wake control with the same including it, by the addition of the new advanced control algorithm. The results have been analysed from the economic and environmental points of view. The main conclusion derived from the exercise is that the impact of the new control system is quite small compared to the initial expectation although there are still some doubts in terms of the failure rates calculations difficult to estimate in a simulation. The reference scenario was an offshore wind farm with a total power of 800 MW using DTU turbines of 10 MW RWT and taken as example, the Norcowe Wind farm in the North Sea.

From the economic viewpoint, the new control algorithms transfer loads to the secondary turbines which receive additional inflow wind. Although this wind is a best quality one (with less turbulences) and consequently equilibrate the bending moments in the blades on second line turbines (reducing tensions), this effect cannot offset the failure rates increased by the rise of the loads. Therefore, the failure rates are slightly higher than expected generating additional failures than the base case and increasing the Operation and Maintenance activities. In parallel, the increase in the average loads improves the Annual Energy Production of the Wind farm providing additional kWh.

Considering the costs at present value, the increase in the O&M operations suppose around € 3.6 Million (for 25 Years), really a small quantity and the incomes from the extra AEP around € 31.0 Million. Therefore, the gaining during the whole lifetime rounds €27.5 Million that represents the 1,12% of the whole project costs (in present value). In D5.2., we will modify some parameters to estimate potential gaining but in no case this figure will be very representative. The exercise provides an excel sheet to easily verify the assumptions done.

In parallel, the environmental impact has been assessed. Using Gabi software, nine categories of impact has been measured for both options, which comprise abiotic depletion, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, photochemical oxidant creation potential and terrestrial ecotoxicity potential. Impacts were compared with between the Farm with active wake steering control or "Yaw control" and the base case. The results show that "Yaw control" contributes an insignificant impact within each of these impact types (less than 1%) when normalised per 1 kWh of electricity production, in comparison to the "Baseline" case. Indeed, in two categories (Eutrophication potential and acidification potential), the results for the “Yaw” scenario were even worst that the “base” scenario. The environmental results are affected by the increase of the O&M operations requiring additional spare parts, vessels, mobilizations, crew, etc.

Finally, the lifetime extension analysis shows that the hub would be most affected by the controlled system, deriving in a reduction of 1.5 years. The study reflects the influence of the crosswind component on the turbine in the yawed position and the emerging additional load cycles. However, these results are in accordance with previous findings of the project of an increasing failure rate and it is expected that the extra maintenance activities will eliminate this lifetime reduction. In summary, results are reasonable although additional research is needed to verify the wake effects.

# 8 APPENDIX A: LIFE CYCLE COSTING

## 8.1 Cables and Protection calculations

| REFERENCE BOTTOM FIX (NON CONTROLLED AND YAW SCENARIOS) | | | | | | |
|---|---|---|---|---|---|---|
| **nº Turbines** | 80 | | Units | **Depth** | 23 | m |
| **Nominal Capacity** | 10 | | MW | **Nº Offshore** | 2 | units |
| **Total Capacity** | 800 | | MW | **Nº Onshore** | 1 | units |
| **Distance to coast** | 80 | | m | **Foundation** | Jackets | |
| | | | | **&/Unit** | **&** | **€** |
| **CONCEPT** | **Nº** | | **Units** | **Unit cost/km** | **Cost (&)** | **Cost (€)** |
| *220 kV, 1x3-core, 1600 mm² Al-XLPE (offshore* | 149.0 | | Km | £642,000 | £95,658,000 | 108,093,540 € |
| *220 kV, 3x1-core, 2500 mm² Al-XLPE (onshore)* | 18.0 | | Km | £1,003,125 | £18,056,250 | 20,403,563 € |
| *220 kV, 3x1-core, 2500 mm² Cu-XLPE (landfall)* | 5.6 | | Km | £1,003,125 | £5,617,500 | 6,347,775 € |
| **TOTAL Export Cable** | | **172.6** | **km** | **£2,648,250** | **£119,331,750** | **£134,844,878** |
| *66 kV, 3-core, 95 mm² Cu-XLPE* | 240.0 | | km | £240,000 | £57,600,000 | 65,088,000 € |
| *66 kV, 3-core, 240 mm² Cu-XLPE* | 17.0 | | km | £300,000 | £5,100,000 | 5,763,000 € |
| *66 kV, 3-core, 400 mm² Cu-XLPE* | 8.8 | | km | £400,000 | £3,520,000 | 3,977,600 € |
| *66 kV, 3-core, 630 mm² Cu-XLPE* | 5.6 | | km | £500,000 | £2,800,000 | 3,164,000 € |
| **TOTAL Array Cable** | | **271.4** | **km** | **£1,440,000** | **£69,020,000** | **77,992,600 €** |
| TOTAL (km) | | | | | **£188,351,750** | **212,837,478 €** |
| Protection | Protection | | 80 | Turb | £1,600,000 | 1,808,000 € |
| TOTAL CABLE & PROTECTIONS | TOTAL | | | | £189,951,750 | 214,645,478 € |

**Table 38. Data for the calculation of cables and protection costs in both scenarios**

| **JACKETS** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **CALCULATIONS JACKET FOUNDATION COSTS** | | | | | | | | **Unitary Cost** | **Total Cost** |
| Available Data | BVGA (100 Turbines /10 MW/1GW) (&) | **£310,000,000** | **£3,100,000** | **Jackets** | 45 m depth | 3,100,000 | &/jacket | **3,503,000 €** | |
| | REFERENCE 80 Turb /10MW /800 MW (&) | **£248,000,000** | **£3,100,000** | **Jackets** | 23 m depth | 1,584,444 | &/Jacket | **1,790,422 €** | **143,233,778 €** |
| **CORROSION** | | | | | | | | | |
| | BVGA (100 Turbines /10 MW/1GW) (&) | **£30,000,000** | **£300,000** | Corr/jacket | | | | £339,000 | |
| | REFERENCE 80 Turb /10MW /800 MW (&) | **£24,000,000** | **£300,000** | Corr/jacket | Depth does not affect | | | **339,000 €** | **27,120,000 €** |

**Table 39. Data for the calculation of jackets and corrosion costs in both scenarios**

## 8.2 Installation Costs

| BVGA AVAILABLE DATA | | | | | | |
|---|---|---|---|---|---|---|
| **nº Turbines** | 100 | Units | **Depth** | 30 | m | |
| **Nominal Capacity** | 10 | MW | **Nº Offshore subst** | 3 | units | |
| **Total Capacity** | 1,000 | MW | **Nº Onshore subst** | 1 | units | |
| **Distance to coast** | 60 | m | | | | |
| **CONCEPT** | | | **Unit cost** | **Nº** | **Total &** | **Total €** |
| **Export Cable installation (on and off)** | | | 325,000 | 210 | £68,250,000 | 77,122,500 € |
| **Array Cable offs. (trench, burial, pull in)** | | | 400,000 | 130 | £52,000,000 | 58,760,000 € |
| **TOTAL CABLE INSTALLATION** | | | | **340** | **£120,250,000** | **135,882,500 €** |
| | | | | *Reference* | *£120,000,000* | |
| **Turbine Installation and commissioning** | | | £500,000 | 100 | £50,000,000 | 56,500,000 € |
| **Foundation installation and commissioning** | | | £1,000,000 | 100 | £100,000,000 | 113,000,000 € |
| **Offshore Substation installation and commissioning** | | | £25,000,000 | 3 | £75,000,000 | 84,750,000 € |
| **Onshore Substation installation and commissioning** | | | £25,000,000 | 1 | £25,000,000 | 28,250,000 € |
| **Offshore logistics** | | | £3,500,000 | 1 | £3,500,000 | 3,955,000 € |
| **TOTAL STRUCTURE INSTALLATION AND COMMISSIONING** | | | | | **£253,500,000** | **286,455,000 €** |

Table 40. Reference data for the Installation costs from the BVGA Report (in &)

| REFERENCE BOTTOM FIX (NON CONTROLLED AND YAW) | | | | | | |
|---|---|---|---|---|---|---|
| nº Turbines | nº Turbines | 80 | Units | Depth | 23 | m |
| Nominal Capacity | Nominal Capacity | 10 | MW | Nº Offshore subst | 2 | units |
| Total Capacity | Total Capacity | 800 | MW | Nº Onshore subst | 1 | units |
| Distance to coast | Distance to coast | 80 | m | Foundation | Jacket | |

| CONCEPT | Unit cost | Nº | Total & | Total € |
|---|---|---|---|---|
| Export Cable installation (on and off) | 325,000 | 173 | £56,095,000 | 63,387,350 € |
| Array Cable offs. (trench, burial, pull in) | 480,000 | 271 | £130,272,000 | 147,207,360 € |
| TOTAL CABLE INSTALLATION | | 444 | £186,367,000 | 210,594,710 € |
| | | | | |
| Turbine Installation and commissioning | £500,000 | 80 | £40,000,000 | 45,200,000 € |
| Foundation installation and commissioning | £1,500,000 | 80 | £120,000,000 | 135,600,000 € |
| Offshore Substation installation and commissioning | £20,000,000 | 2 | £40,000,000 | 45,200,000 € |
| Onshore Substation installation and commissioning | £20,000,000 | 1 | £20,000,000 | 22,600,000 € |
| Offshore logistics | £2,800,000 | 1 | £2,800,000 | 3,164,000 € |
| TOTAL STRUCTURE INSTALLATION AND COMMISSIONING | | | £222,800,000 | 251,764,000 € |

Table 41. Installation costs adapted to the Base/yaw scenario (in €)

## 8.3 Operation and Maintenance

### 8.3.1 Data for the calculation of the O&M in the base scenario

| UNPLANNED MAINTENANCE | BASE | | |
|---|---|---|---|
| Nº OF REPAIRS /25 YEARS | Minor repair | Major repair | Replacement |
| Gearbox | 665.28 | 165.73 | 28.68 |
| Generator | 50.35 | 18.03 | 9.13 |
| Electrical system | 387.90 | 44.30 | 1.80 |
| Pitch system | 413.93 | 20.00 | 8.68 |
| Yaw system | 270.95 | 37.85 | 12.88 |
| Blades | 203.15 | 46.95 | 43.68 |
| Main shaft | 240.63 | 28.38 | 8.83 |
| TOTAL | 2,232.18 | 361.23 | 113.65 |

Table 42. BASE. Unplanned maintenance (Nº Repairs)

| MATERIAL COSTS | BASE | | |
|---|---|---|---|
| Description | Minor repair | Major repair | Replacement |
| Gearbox | 5,000 € | 26,670 € | 592,500 € |
| Generator | 1,000 € | 14,340 € | 236,500 € |
| Electrical system | 1,000 € | 5,000 € | 50,000 € |
| Pitch system | 500 € | 1,900 € | 14,000 € |
| Yaw system | 500 € | 3,000 € | 12,500 € |
| Blades | 5,000 € | 43,110 € | 445,000 € |
| Main shaft | 1,000 € | 14,000 € | 232,000 € |

Table 43. BASE. Unplanned Maintenance. (Material Costs)

| PLANNED MAINTENANCE | BASE | | |
|---|---|---|---|
| Interval | 1/year/turbine | Material cost | 5,000 |

**Table 44. BASE. Planned Maintenance. Cost of material**

| VESSELS USED | BASE | |
|---|---|---|
| CTV | JUV | distance to shore (km) |
| 7,615 | 2,462 | 80 |

| TECHNICIANS USED (h) BASE |
|---|
| 119,274 |

**Table 45. BASE. Number of vessels and time spent by technicians for maintenance**

### 8.3.2 Data for the calculation of the O&M in the yaw scenario

| UNPLANNED MAINTENANCE | YAW | | |
|---|---|---|---|
| Nº OF REPAIRS /25 YEARS | Minor repair | Major repair | Replacement |
| Gearbox | 672.08 | 162.65 | 30.68 |
| Generator | 53.20 | 18.50 | 8.65 |
| Electrical system | 382.88 | 46.85 | 1.80 |
| Pitch system | 410.43 | 21.25 | 8.33 |
| Yaw system | 272.03 | 37.75 | 11.50 |
| Blades | 210.20 | 48.53 | 43.45 |
| Main shaft | 250.10 | 27.90 | 9.50 |
| TOTAL | 2,250.90 | 363.43 | 113.90 |

**Table 46. YAW. Unplanned maintenance (Nº Repairs)**

| MATERIAL COSTS | YAW | | |
|---|---|---|---|
| Description | Minor repair | Major repair | Replacement |
| Gearbox | 5,000 € | 26,670 € | 592,500 € |
| Generator | 1,000 € | 14,340 € | 236,500 € |
| Electrical system | 1,000 € | 5,000 € | 50,000 € |
| Pitch system | 500 € | 1,900 € | 14,000 € |
| Yaw system | 500 € | 3,000 € | 12,500 € |
| Blades | 5,000 € | 43,110 € | 445,000 € |
| Main shaft | 1,000 € | 14,000 € | 232,000 € |

**Table 47. YAW. Unplanned Maintenance. (Material Costs)**

| PLANNED MAINTENANCE | YAW | | |
|---|---|---|---|
| Interval | 1/year/turbine | Material cost | 5,000 |

**Table 48. YAW. Planned Maintenance. Cost of material**

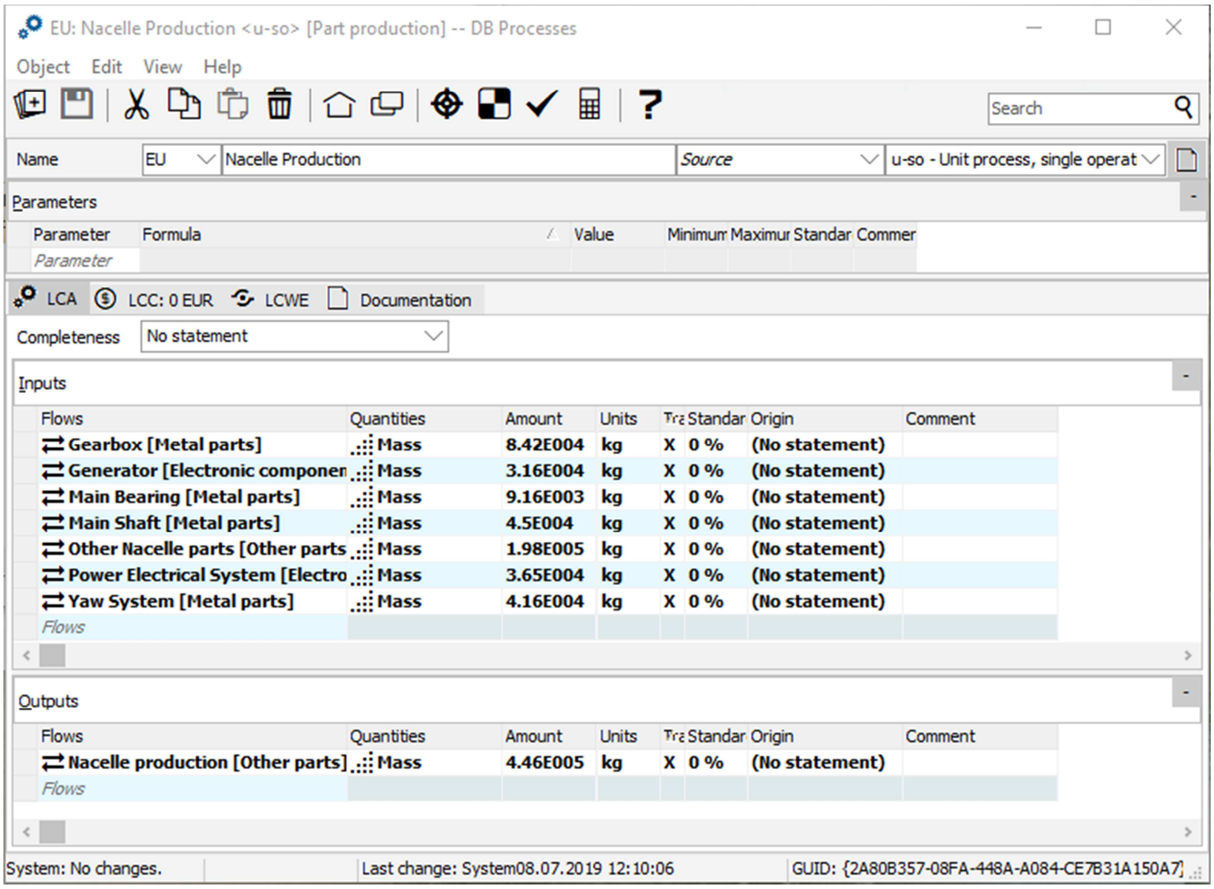
| VESSELS USED | YAW | |
|---|---|---|
| CTV | JUV | distance to shore (km) |
| 7,752 | 2,583 | 80 |

| TECHNICIANS USED (h) YAW |
|---|
| 121,925 |

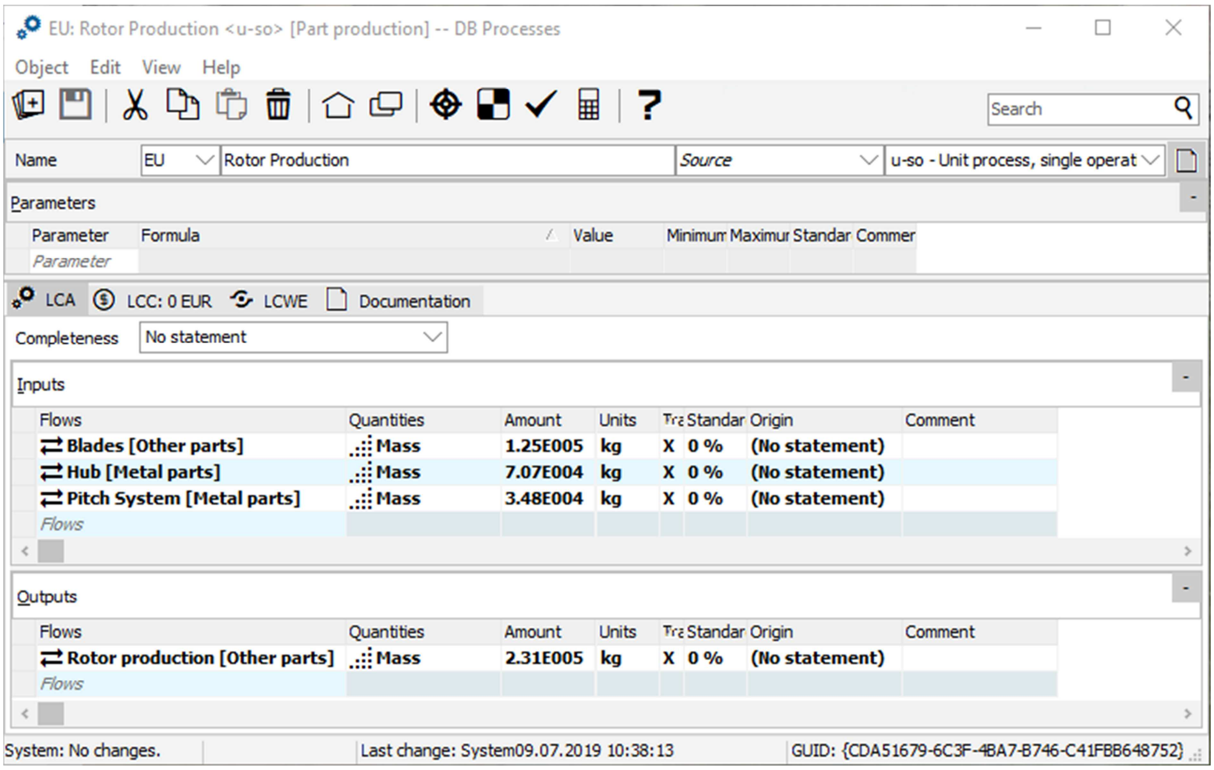
**Table 49. YAW. Number of vessels and time spent by technicians for**

# 9 APPENDIX B: LIFE CYCLE ANALYSIS. PROCESSES FOR WIND PLANT STAGES

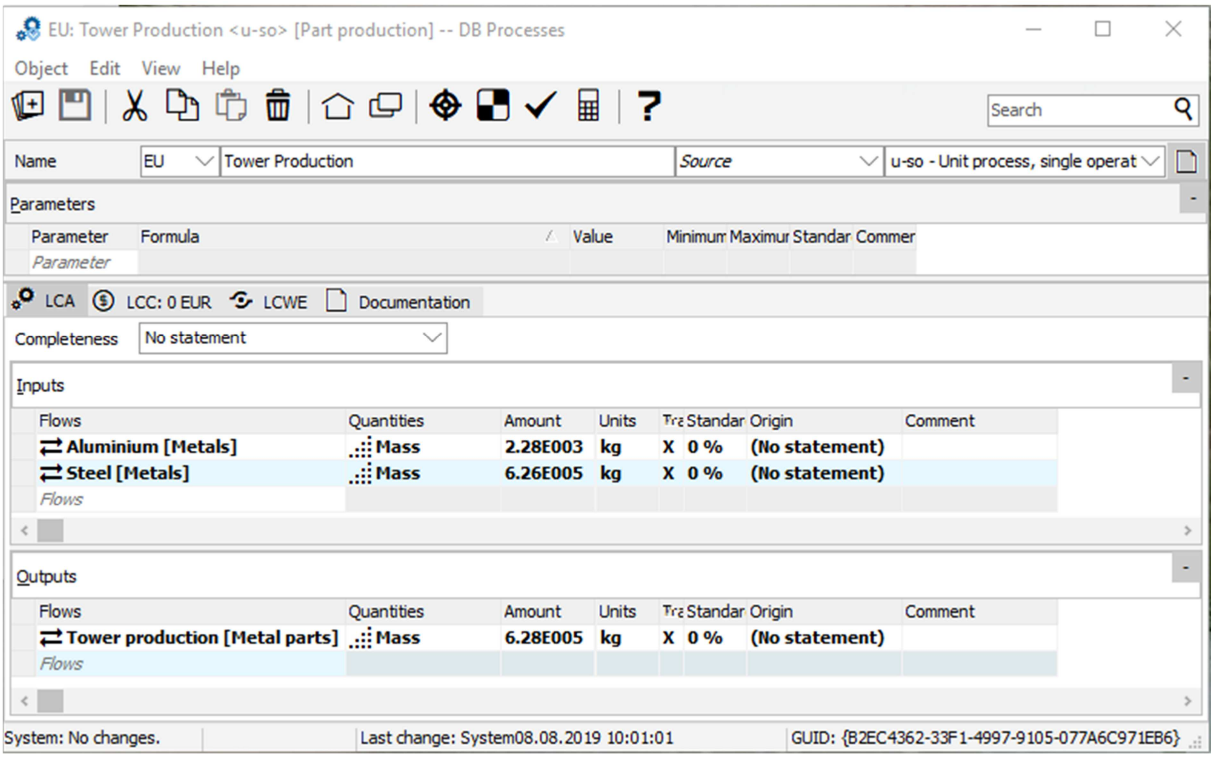
## 9.1 Production stage: Nacelle



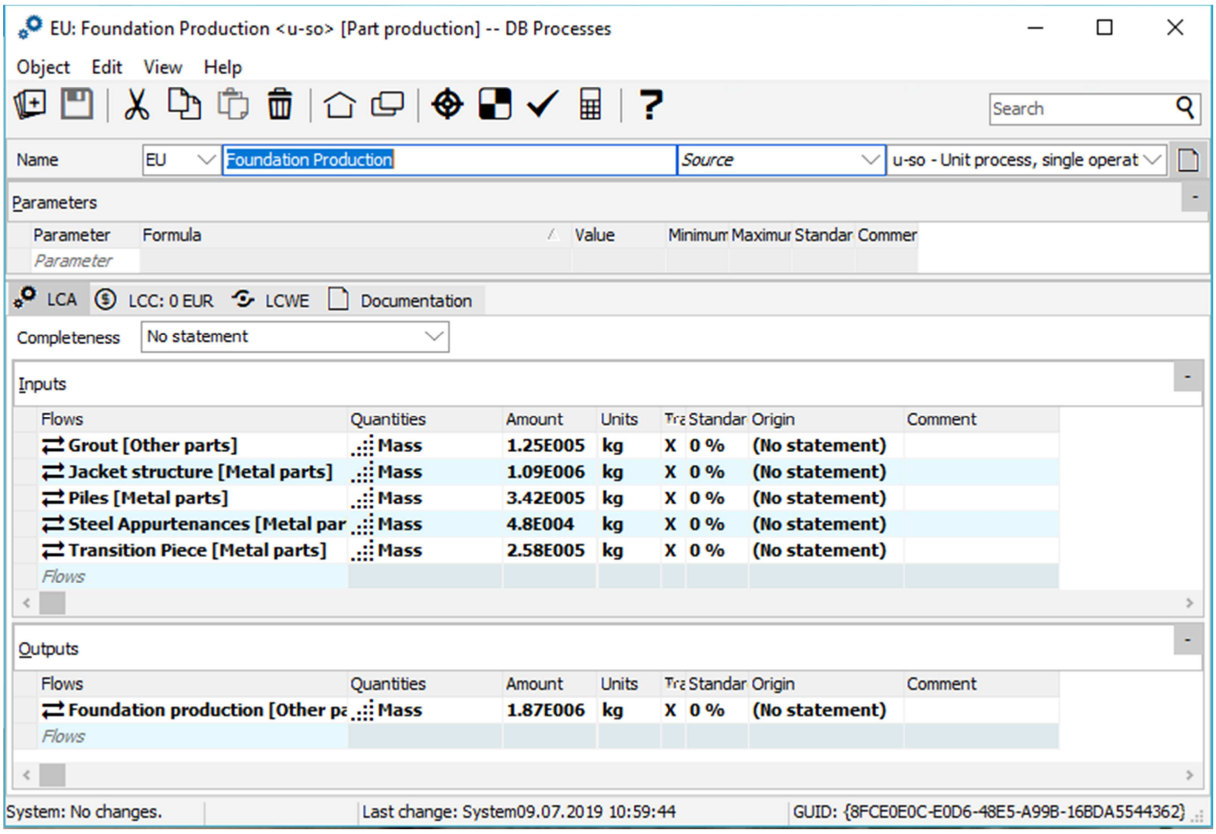
## 9.2 Production stage: Rotor



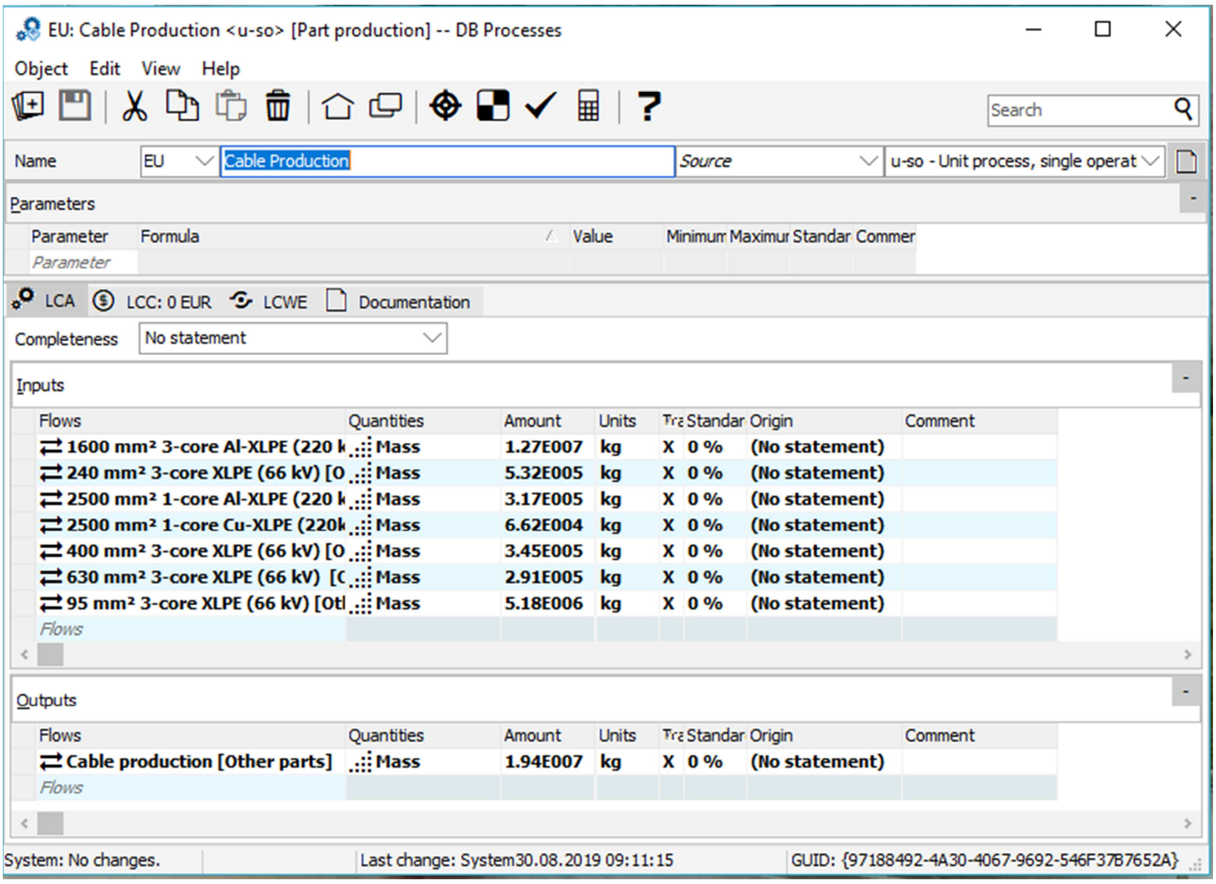
## 9.3 Production stage: Tower



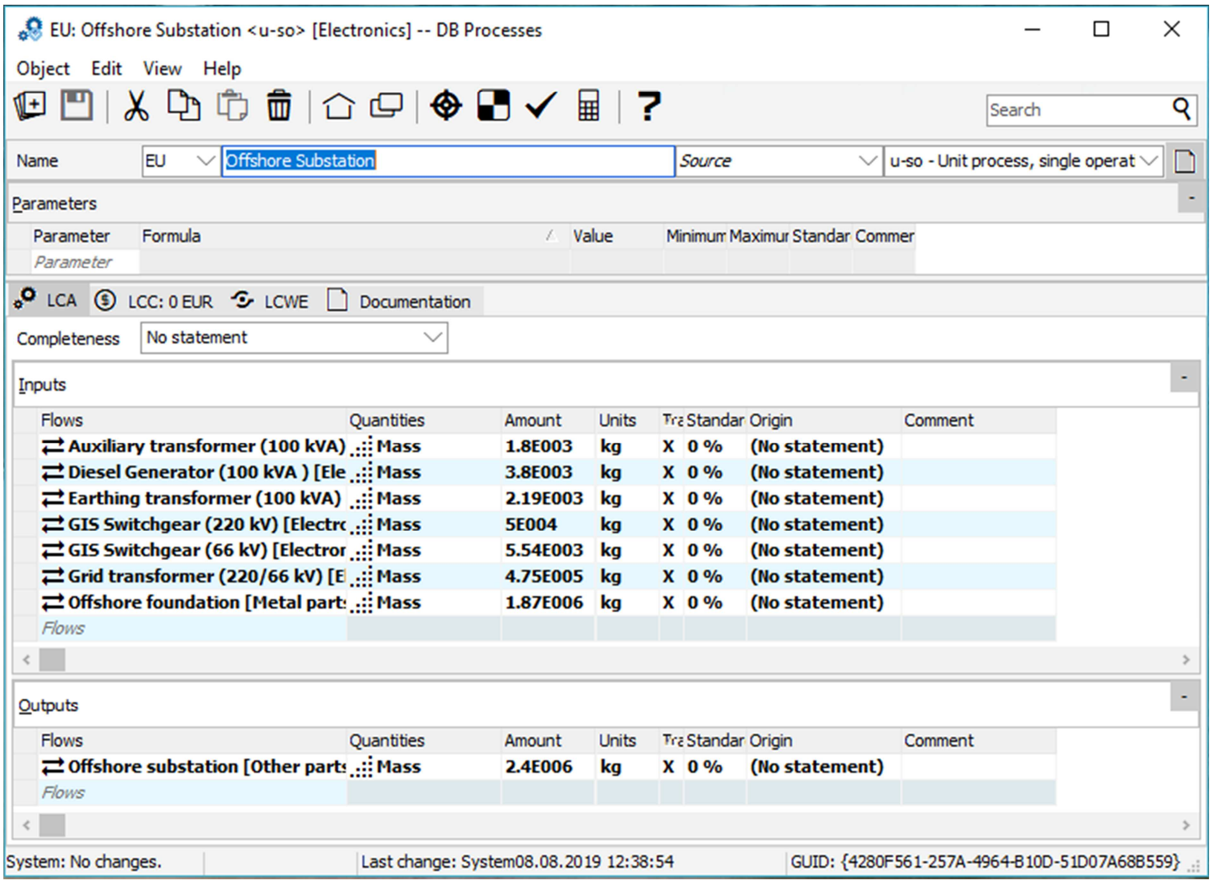
## 9.4 Production stage: Foundation



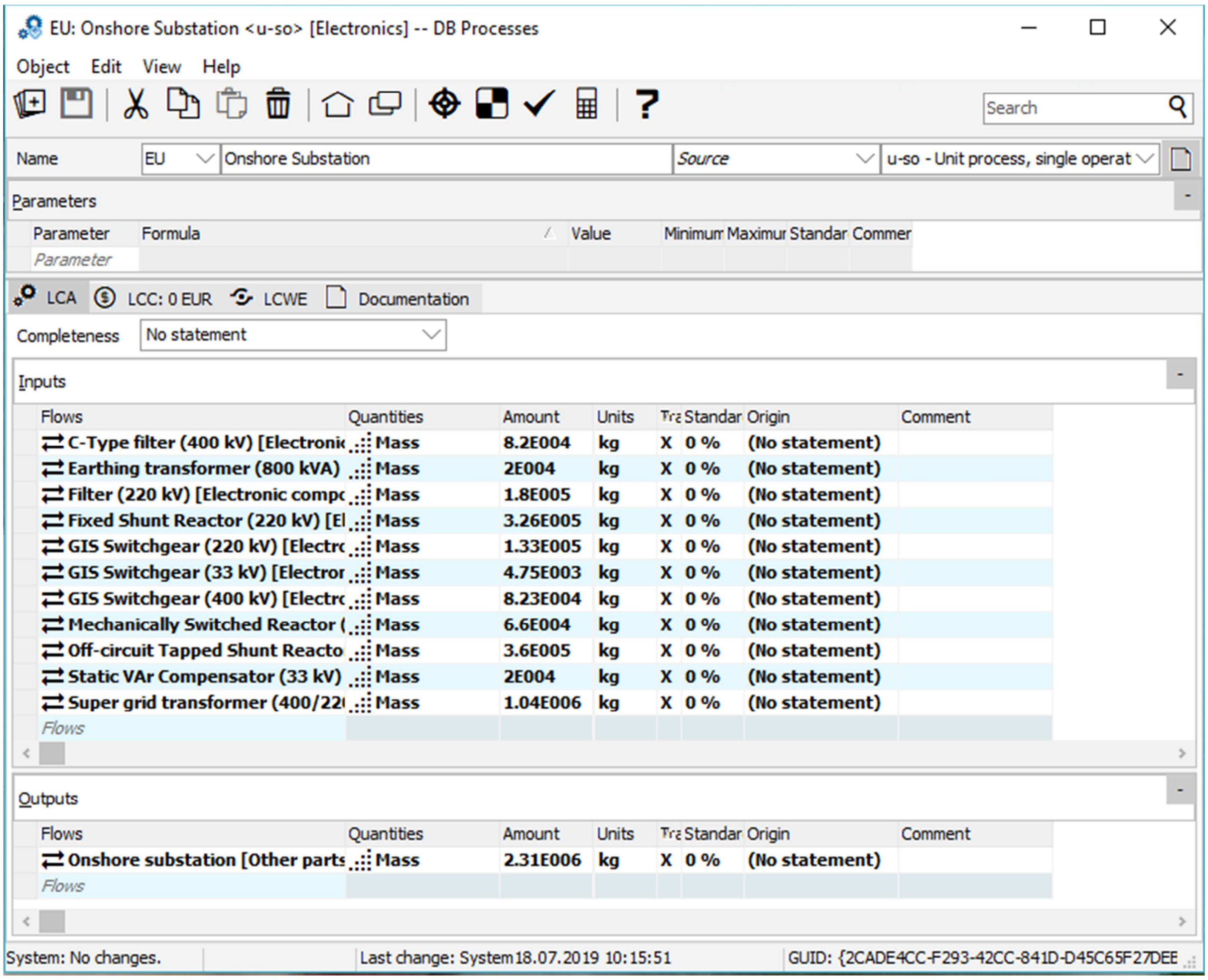
## 9.5 Production stage: Cable



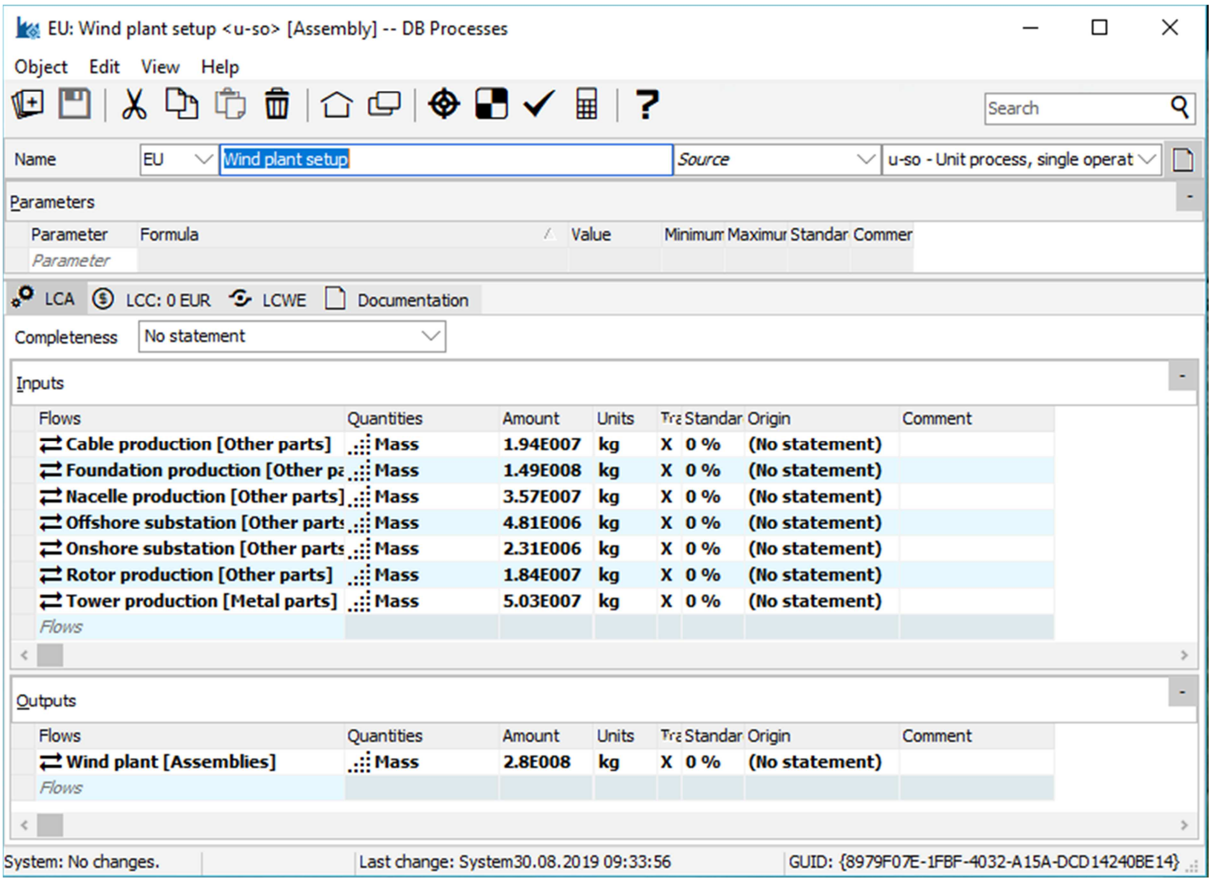
## 9.6 Production stage: Offshore substation



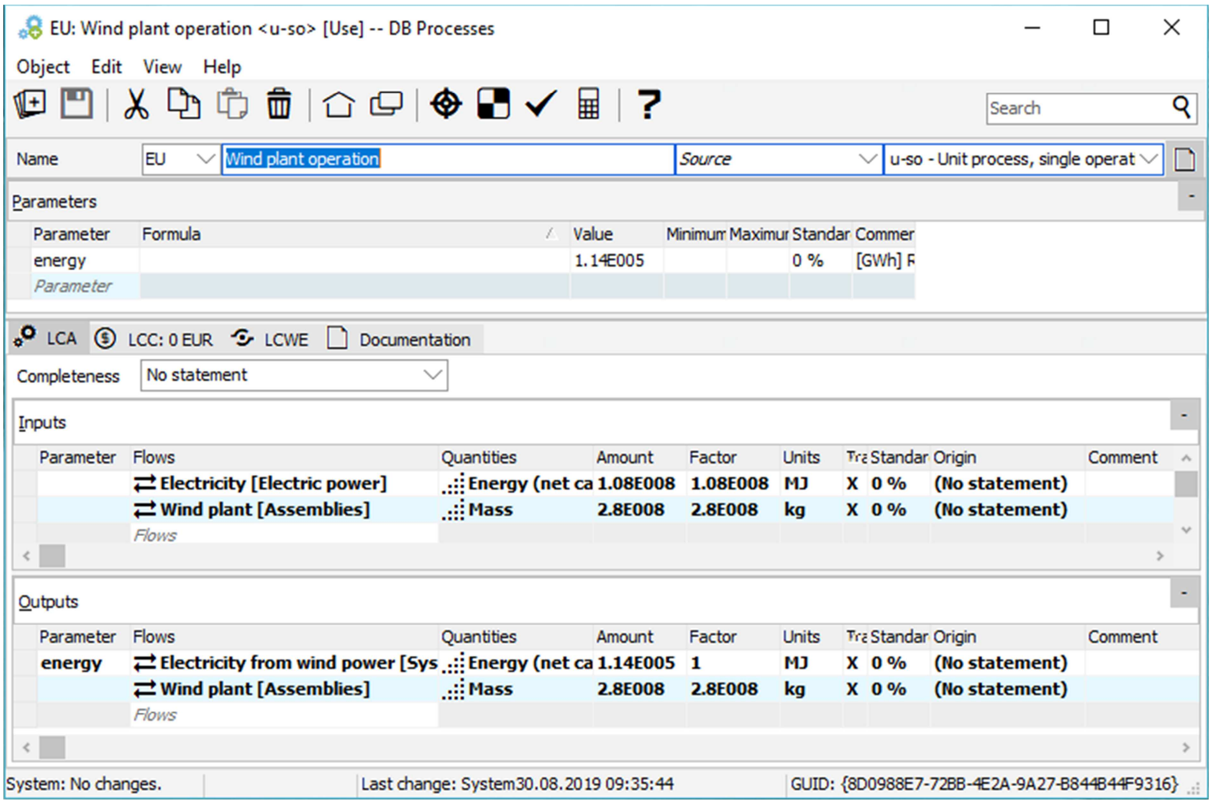
## 9.7 Production stage: Onshore substation



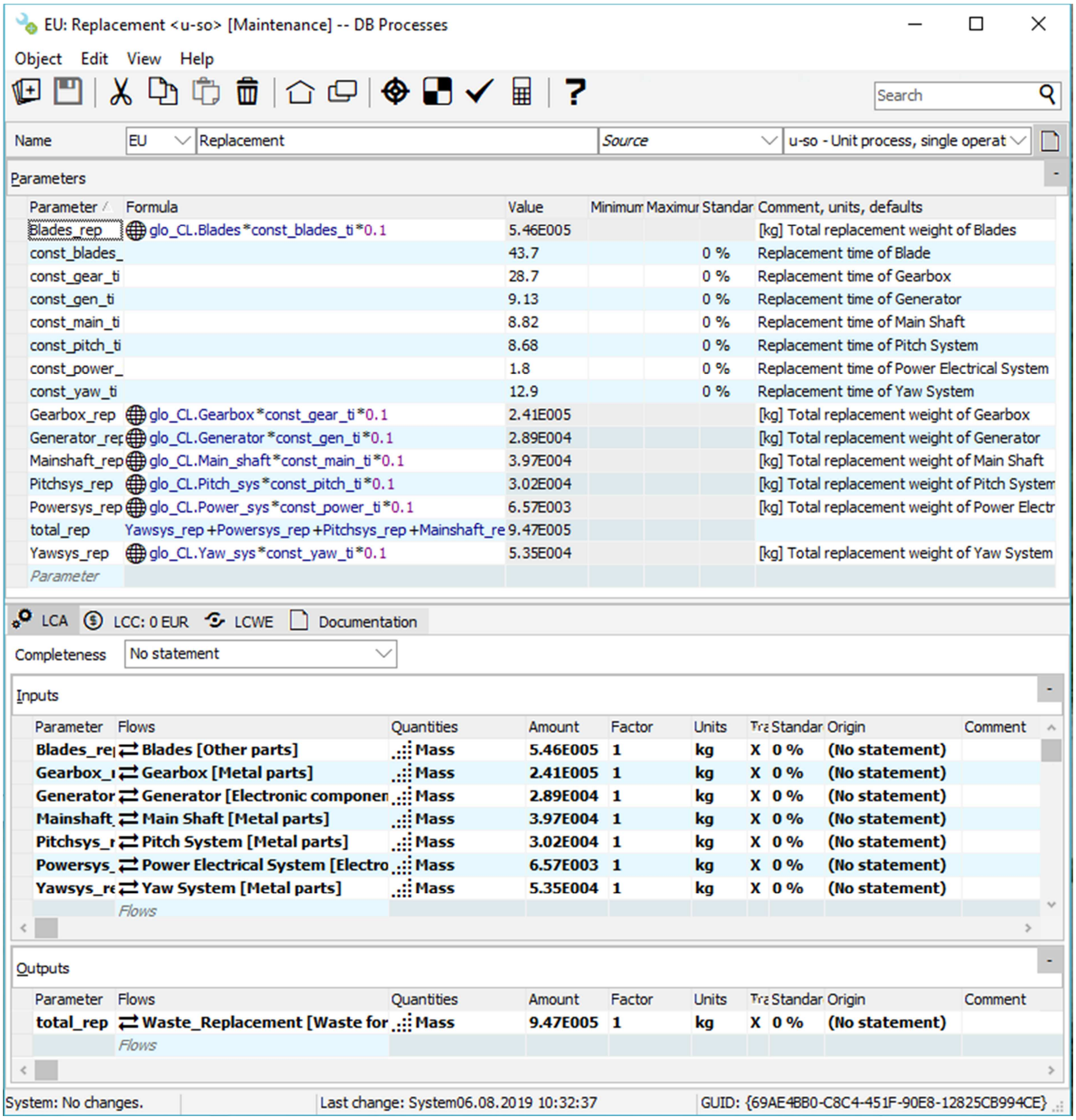
## 9.8 Setup stage



## 9.9 O&M stage: Operation



## 9.10 O&M stage: Replacement



EU: Replacement <u-so> [Maintenance] -- DB Processes

Object Edit View Help

Name: EU | Replacement | Source | u-so - Unit process, single operat

Parameters

| Parameter | Formula | Value | Minimum | Maximum | Standar | Comment, units, defaults |
|---|---|---|---|---|---|---|
| Blades_rep | glo_CL.Blades*const_blades_ti*0.1 | 5.46E005 | | | | [kg] Total replacement weight of Blades |
| const_blades_ | | 43.7 | | | 0 % | Replacement time of Blade |
| const_gear_ti | | 28.7 | | | 0 % | Replacement time of Gearbox |
| const_gen_ti | | 9.13 | | | 0 % | Replacement time of Generator |
| const_main_ti | | 8.82 | | | 0 % | Replacement time of Main Shaft |
| const_pitch_ti | | 8.68 | | | 0 % | Replacement time of Pitch System |
| const_power_ | | 1.8 | | | 0 % | Replacement time of Power Electrical System |
| const_yaw_ti | | 12.9 | | | 0 % | Replacement time of Yaw System |
| Gearbox_rep | glo_CL.Gearbox*const_gear_ti*0.1 | 2.41E005 | | | | [kg] Total replacement weight of Gearbox |
| Generator_rep | glo_CL.Generator*const_gen_ti*0.1 | 2.89E004 | | | | [kg] Total replacement weight of Generator |
| Mainshaft_rep | glo_CL.Main_shaft*const_main_ti*0.1 | 3.97E004 | | | | [kg] Total replacement weight of Main Shaft |
| Pitchsys_rep | glo_CL.Pitch_sys*const_pitch_ti*0.1 | 3.02E004 | | | | [kg] Total replacement weight of Pitch System |
| Powersys_rep | glo_CL.Power_sys*const_power_ti*0.1 | 6.57E003 | | | | [kg] Total replacement weight of Power Electr |
| total_rep | Yawsys_rep+Powersys_rep+Pitchsys_rep+Mainshaft_re | 9.47E005 | | | | |
| Yawsys_rep | glo_CL.Yaw_sys*const_yaw_ti*0.1 | 5.35E004 | | | | [kg] Total replacement weight of Yaw System |
| Parameter | | | | | | |

LCA LCC: 0 EUR LCWE Documentation

Completeness: No statement

Inputs

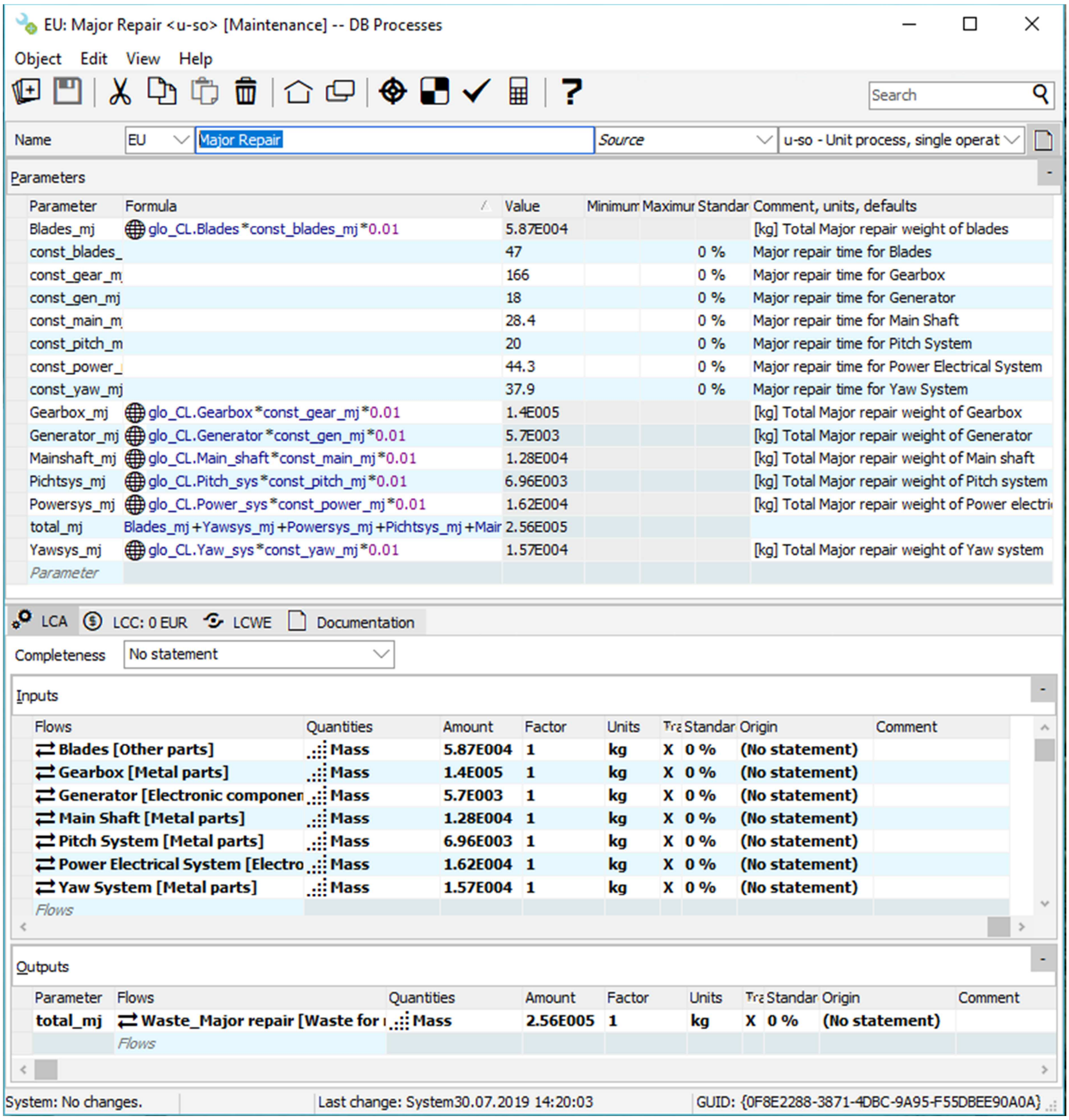
| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| Blades_re | Blades [Other parts] | Mass | 5.46E005 | 1 | kg | X | 0 % | (No statement) | |
| Gearbox_ | Gearbox [Metal parts] | Mass | 2.41E005 | 1 | kg | X | 0 % | (No statement) | |
| Generator | Generator [Electronic componen | Mass | 2.89E004 | 1 | kg | X | 0 % | (No statement) | |
| Mainshaft_ | Main Shaft [Metal parts] | Mass | 3.97E004 | 1 | kg | X | 0 % | (No statement) | |
| Pitchsys_ | Pitch System [Metal parts] | Mass | 3.02E004 | 1 | kg | X | 0 % | (No statement) | |
| Powersys_ | Power Electrical System [Electro | Mass | 6.57E003 | 1 | kg | X | 0 % | (No statement) | |
| Yawsys_re | Yaw System [Metal parts] | Mass | 5.35E004 | 1 | kg | X | 0 % | (No statement) | |
| | Flows | | | | | | | | |

Outputs

| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| total_rep | Waste_Replacement [Waste for | Mass | 9.47E005 | 1 | kg | X | 0 % | (No statement) | |
| | Flows | | | | | | | | |

System: No changes. Last change: System06.08.2019 10:32:37 GUID: {69AE4BB0-C8C4-451F-90E8-12825CB994CE}

## 9.11 O&M stage: Major repair



EU: Major Repair <u-so> [Maintenance] -- DB Processes

Object Edit View Help

Name: EU | Major Repair | Source | u-so - Unit process, single operat

Parameters

| Parameter | Formula | Value | Minimum | Maximum | Standard | Comment, units, defaults |
|---|---|---|---|---|---|---|
| Blades_mj | glo_CL.Blades*const_blades_mj*0.01 | 5.87E004 | | | | [kg] Total Major repair weight of blades |
| const_blades_ | | 47 | | | 0 % | Major repair time for Blades |
| const_gear_m | | 166 | | | 0 % | Major repair time for Gearbox |
| const_gen_mj | | 18 | | | 0 % | Major repair time for Generator |
| const_main_m | | 28.4 | | | 0 % | Major repair time for Main Shaft |
| const_pitch_m | | 20 | | | 0 % | Major repair time for Pitch System |
| const_power_ | | 44.3 | | | 0 % | Major repair time for Power Electrical System |
| const_yaw_mj | | 37.9 | | | 0 % | Major repair time for Yaw System |
| Gearbox_mj | glo_CL.Gearbox*const_gear_mj*0.01 | 1.4E005 | | | | [kg] Total Major repair weight of Gearbox |
| Generator_mj | glo_CL.Generator*const_gen_mj*0.01 | 5.7E003 | | | | [kg] Total Major repair weight of Generator |
| Mainshaft_mj | glo_CL.Main_shaft*const_main_mj*0.01 | 1.28E004 | | | | [kg] Total Major repair weight of Main shaft |
| Pichtsys_mj | glo_CL.Pitch_sys*const_pitch_mj*0.01 | 6.96E003 | | | | [kg] Total Major repair weight of Pitch system |
| Powersys_mj | glo_CL.Power_sys*const_power_mj*0.01 | 1.62E004 | | | | [kg] Total Major repair weight of Power electri |
| total_mj | Blades_mj+Yawsys_mj+Powersys_mj+Pichtsys_mj+Mair | 2.56E005 | | | | |
| Yawsys_mj | glo_CL.Yaw_sys*const_yaw_mj*0.01 | 1.57E004 | | | | [kg] Total Major repair weight of Yaw system |
| *Parameter* | | | | | | |

LCA | LCC: 0 EUR | LCWE | Documentation

Completeness: No statement

Inputs

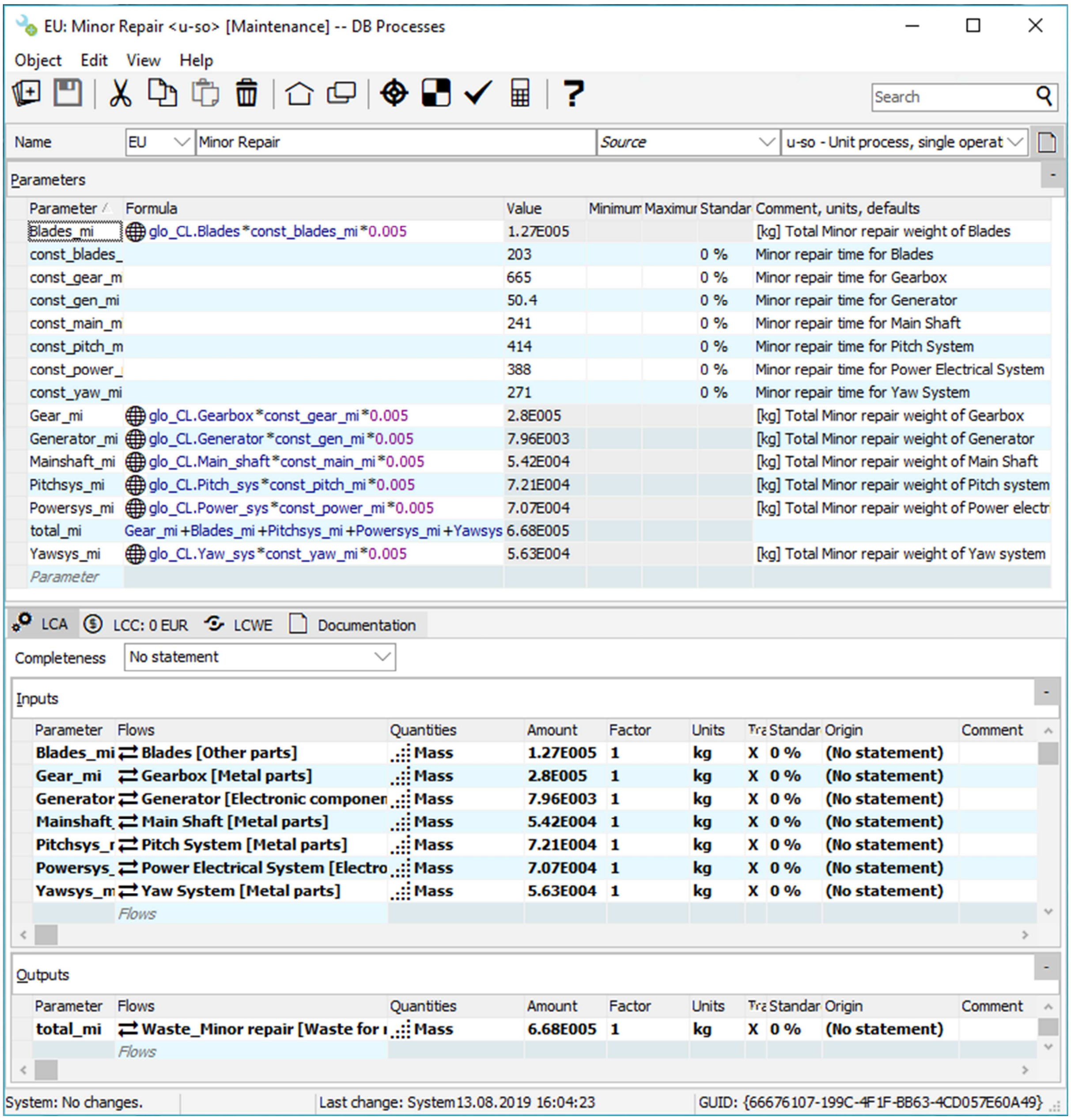
| Flows | Quantities | Amount | Factor | Units | Tra | Standard | Origin | Comment |
|---|---|---|---|---|---|---|---|---|
| Blades [Other parts] | Mass | 5.87E004 | 1 | kg | X | 0 % | (No statement) | |
| Gearbox [Metal parts] | Mass | 1.4E005 | 1 | kg | X | 0 % | (No statement) | |
| Generator [Electronic componen | Mass | 5.7E003 | 1 | kg | X | 0 % | (No statement) | |
| Main Shaft [Metal parts] | Mass | 1.28E004 | 1 | kg | X | 0 % | (No statement) | |
| Pitch System [Metal parts] | Mass | 6.96E003 | 1 | kg | X | 0 % | (No statement) | |
| Power Electrical System [Electro | Mass | 1.62E004 | 1 | kg | X | 0 % | (No statement) | |
| Yaw System [Metal parts] | Mass | 1.57E004 | 1 | kg | X | 0 % | (No statement) | |
| *Flows* | | | | | | | | |

Outputs

| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standard | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| total_mj | Waste_Major repair [Waste for | Mass | 2.56E005 | 1 | kg | X | 0 % | (No statement) | |
| | *Flows* | | | | | | | | |

System: No changes. | Last change: System30.07.2019 14:20:03 | GUID: {0F8E2288-3871-4DBC-9A95-F55DBEE90A0A}

## 9.12 O&M stage: Minor repair




| Parameter | Formula | Value | Minimum | Maximum | Standar | Comment, units, defaults |
|---|---|---|---|---|---|---|
| Blades_mi | glo_CL.Blades*const_blades_mi*0.005 | 1.27E005 | | | | [kg] Total Minor repair weight of Blades |
| const_blades_ | | 203 | | | 0 % | Minor repair time for Blades |
| const_gear_m | | 665 | | | 0 % | Minor repair time for Gearbox |
| const_gen_mi | | 50.4 | | | 0 % | Minor repair time for Generator |
| const_main_m | | 241 | | | 0 % | Minor repair time for Main Shaft |
| const_pitch_m | | 414 | | | 0 % | Minor repair time for Pitch System |
| const_power_ | | 388 | | | 0 % | Minor repair time for Power Electrical System |
| const_yaw_mi | | 271 | | | 0 % | Minor repair time for Yaw System |
| Gear_mi | glo_CL.Gearbox*const_gear_mi*0.005 | 2.8E005 | | | | [kg] Total Minor repair weight of Gearbox |
| Generator_mi | glo_CL.Generator*const_gen_mi*0.005 | 7.96E003 | | | | [kg] Total Minor repair weight of Generator |
| Mainshaft_mi | glo_CL.Main_shaft*const_main_mi*0.005 | 5.42E004 | | | | [kg] Total Minor repair weight of Main Shaft |
| Pitchsys_mi | glo_CL.Pitch_sys*const_pitch_mi*0.005 | 7.21E004 | | | | [kg] Total Minor repair weight of Pitch system |
| Powersys_mi | glo_CL.Power_sys*const_power_mi*0.005 | 7.07E004 | | | | [kg] Total Minor repair weight of Power electr |
| total_mi | Gear_mi+Blades_mi+Pitchsys_mi+Powersys_mi+Yawsys | 6.68E005 | | | | |
| Yawsys_mi | glo_CL.Yaw_sys*const_yaw_mi*0.005 | 5.63E004 | | | | [kg] Total Minor repair weight of Yaw system |
| Parameter | | | | | | |

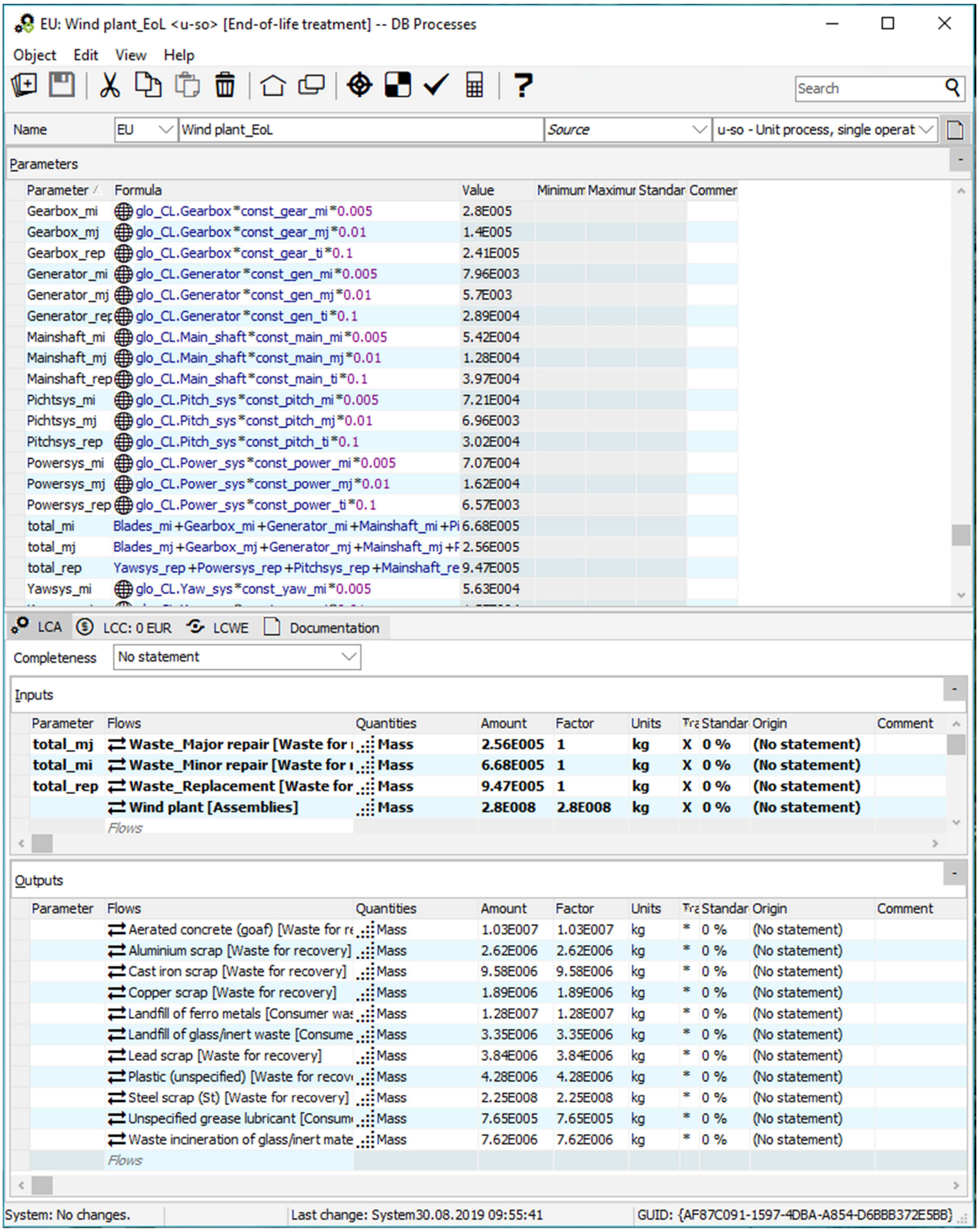


| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| Blades_mi | Blades [Other parts] | Mass | 1.27E005 | 1 | kg | X | 0 % | (No statement) | |
| Gear_mi | Gearbox [Metal parts] | Mass | 2.8E005 | 1 | kg | X | 0 % | (No statement) | |
| Generator | Generator [Electronic componen | Mass | 7.96E003 | 1 | kg | X | 0 % | (No statement) | |
| Mainshaft_ | Main Shaft [Metal parts] | Mass | 5.42E004 | 1 | kg | X | 0 % | (No statement) | |
| Pitchsys_r | Pitch System [Metal parts] | Mass | 7.21E004 | 1 | kg | X | 0 % | (No statement) | |
| Powersys_ | Power Electrical System [Electro | Mass | 7.07E004 | 1 | kg | X | 0 % | (No statement) | |
| Yawsys_m | Yaw System [Metal parts] | Mass | 5.63E004 | 1 | kg | X | 0 % | (No statement) | |
| | Flows | | | | | | | | |



| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| total_mi | Waste_Minor repair [Waste for r | Mass | 6.68E005 | 1 | kg | X | 0 % | (No statement) | |
| | Flows | | | | | | | | |

## 9.13 End of life stage



EU: Wind plant_EoL <u-so> [End-of-life treatment] -- DB Processes

Object Edit View Help

Name: EU | Wind plant_EoL | Source | u-so - Unit process, single operat

Parameters

| Parameter | Formula | Value | Minimum | Maximum | Standard | Comment |
|---|---|---|---|---|---|---|
| Gearbox_mi | glo_CL.Gearbox*const_gear_mi*0.005 | 2.8E005 | | | | |
| Gearbox_mj | glo_CL.Gearbox*const_gear_mj*0.01 | 1.4E005 | | | | |
| Gearbox_rep | glo_CL.Gearbox*const_gear_ti*0.1 | 2.41E005 | | | | |
| Generator_mi | glo_CL.Generator*const_gen_mi*0.005 | 7.96E003 | | | | |
| Generator_mj | glo_CL.Generator*const_gen_mj*0.01 | 5.7E003 | | | | |
| Generator_rep | glo_CL.Generator*const_gen_ti*0.1 | 2.89E004 | | | | |
| Mainshaft_mi | glo_CL.Main_shaft*const_main_mi*0.005 | 5.42E004 | | | | |
| Mainshaft_mj | glo_CL.Main_shaft*const_main_mj*0.01 | 1.28E004 | | | | |
| Mainshaft_rep | glo_CL.Main_shaft*const_main_ti*0.1 | 3.97E004 | | | | |
| Pichtsys_mi | glo_CL.Pitch_sys*const_pitch_mi*0.005 | 7.21E004 | | | | |
| Pichtsys_mj | glo_CL.Pitch_sys*const_pitch_mj*0.01 | 6.96E003 | | | | |
| Pitchsys_rep | glo_CL.Pitch_sys*const_pitch_ti*0.1 | 3.02E004 | | | | |
| Powersys_mi | glo_CL.Power_sys*const_power_mi*0.005 | 7.07E004 | | | | |
| Powersys_mj | glo_CL.Power_sys*const_power_mj*0.01 | 1.62E004 | | | | |
| Powersys_rep | glo_CL.Power_sys*const_power_ti*0.1 | 6.57E003 | | | | |
| total_mi | Blades_mi+Gearbox_mi+Generator_mi+Mainshaft_mi+Pi | 6.68E005 | | | | |
| total_mj | Blades_mj+Gearbox_mj+Generator_mj+Mainshaft_mj+F | 2.56E005 | | | | |
| total_rep | Yawsys_rep+Powersys_rep+Pitchsys_rep+Mainshaft_re | 9.47E005 | | | | |
| Yawsys_mi | glo_CL.Yaw_sys*const_yaw_mi*0.005 | 5.63E004 | | | | |

LCA | LCC: 0 EUR | LCWE | Documentation

Completeness: No statement

Inputs

| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| **total_mj** | **Waste_Major repair [Waste for** | **Mass** | **2.56E005** | **1** | **kg** | **X** | **0 %** | **(No statement)** | |
| **total_mi** | **Waste_Minor repair [Waste for** | **Mass** | **6.68E005** | **1** | **kg** | **X** | **0 %** | **(No statement)** | |
| **total_rep** | **Waste_Replacement [Waste for** | **Mass** | **9.47E005** | **1** | **kg** | **X** | **0 %** | **(No statement)** | |
| | **Wind plant [Assemblies]** | **Mass** | **2.8E008** | **2.8E008** | **kg** | **X** | **0 %** | **(No statement)** | |
| | *Flows* | | | | | | | | |

Outputs

| Parameter | Flows | Quantities | Amount | Factor | Units | Tra | Standar | Origin | Comment |
|---|---|---|---|---|---|---|---|---|---|
| | Aerated concrete (goaf) [Waste for re | Mass | 1.03E007 | 1.03E007 | kg | * | 0 % | (No statement) | |
| | Aluminium scrap [Waste for recovery] | Mass | 2.62E006 | 2.62E006 | kg | * | 0 % | (No statement) | |
| | Cast iron scrap [Waste for recovery] | Mass | 9.58E006 | 9.58E006 | kg | * | 0 % | (No statement) | |
| | Copper scrap [Waste for recovery] | Mass | 1.89E006 | 1.89E006 | kg | * | 0 % | (No statement) | |
| | Landfill of ferro metals [Consumer was | Mass | 1.28E007 | 1.28E007 | kg | * | 0 % | (No statement) | |
| | Landfill of glass/inert waste [Consume | Mass | 3.35E006 | 3.35E006 | kg | * | 0 % | (No statement) | |
| | Lead scrap [Waste for recovery] | Mass | 3.84E006 | 3.84E006 | kg | * | 0 % | (No statement) | |
| | Plastic (unspecified) [Waste for recov | Mass | 4.28E006 | 4.28E006 | kg | * | 0 % | (No statement) | |
| | Steel scrap (St) [Waste for recovery] | Mass | 2.25E008 | 2.25E008 | kg | * | 0 % | (No statement) | |
| | Unspecified grease lubricant [Consum | Mass | 7.65E005 | 7.65E005 | kg | * | 0 % | (No statement) | |
| | Waste incineration of glass/inert mate | Mass | 7.62E006 | 7.62E006 | kg | * | 0 % | (No statement) | |
| | *Flows* | | | | | | | | |

System: No changes. | Last change: System30.08.2019 09:55:41 | GUID: {AF87C091-1597-4DBA-A854-D6BBB372E5BB}

# 10 APPENDIX C: LIFE CYCLE INVENTORY

**Table 50: Life cycle inventory of 800 MW offshore wind power plant of 10 MW DTU RWT in different scenario (units shown in mg per kWh)**

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| **Energy resources** | **1.64E+03** | **4.99E+00** | **1.36E+02** | **-2.74E+01** | **1.75E+03** | **1.63E+03** | **4.95E+00** | **1.36E+02** | **-2.72E+01** | **1.74E+03** |
| **Non-renewable energy resources** | **1.64E+03** | **4.99E+00** | **1.36E+02** | **-2.74E+01** | **1.75E+03** | **1.63E+03** | **4.95E+00** | **1.36E+02** | **-2.72E+01** | **1.74E+03** |
| Crude oil | 1.67E+02 | 4.61E+00 | 4.26E+01 | 4.87E+00 | 2.19E+02 | 1.66E+02 | 4.57E+00 | 4.36E+01 | 4.83E+00 | 2.19E+02 |
| Hard coal | 1.32E+03 | 2.63E-02 | 2.49E+01 | -1.31E+01 | 1.33E+03 | 1.31E+03 | 2.61E-02 | 2.48E+01 | -1.30E+01 | 1.32E+03 |
| Lignite | 1.15E+02 | 5.06E-02 | 5.72E+01 | -1.06E+01 | 1.61E+02 | 1.14E+02 | 5.03E-02 | 5.68E+01 | -1.05E+01 | 1.60E+02 |
| Natural gas | 3.61E+01 | 3.01E-01 | 1.08E+01 | -6.83E+00 | 4.04E+01 | 3.58E+01 | 2.99E-01 | 1.08E+01 | -6.78E+00 | 4.02E+01 |
| Peat (resource) | 1.28E-01 | 2.76E-04 | 5.73E-03 | -1.73E+00 | -1.60E+00 | 1.27E-01 | 2.74E-04 | 5.79E-03 | -1.72E+00 | -1.59E+00 |
| Uranium (resource) | 2.38E-03 | 1.14E-06 | 8.85E-04 | -4.60E-04 | 2.81E-03 | 2.36E-03 | 1.14E-06 | 8.79E-04 | -4.56E-04 | 2.79E-03 |
| **Renewable energy resources** | **2.75E-04** | | **2.99E-06** | | **2.78E-04** | **2.73E-04** | | **2.97E-06** | | **2.75E-04** |
| Biomass (MJ) | 2.75E-04 | | 2.99E-06 | | 2.78E-04 | 2.73E-04 | | 2.97E-06 | | 2.75E-04 |
| **Material resources** | **2.46E+06** | **8.91E+02** | **4.14E+05** | **5.31E+03** | **2.87E+06** | **2.44E+06** | **8.84E+02** | **4.11E+05** | **5.28E+03** | **2.85E+06** |
| **Non-renewable elements** | **1.87E+03** | **2.16E-03** | **6.07E+00** | **2.12E-01** | **1.87E+03** | **1.85E+03** | **5.46E-03** | **6.11E+00** | **2.10E-01** | **1.86E+03** |
| Antimony | 4.23E-06 | 6.16E-07 | 1.50E-06 | 7.04E-07 | 7.04E-06 | 4.19E-06 | 6.12E-07 | 1.49E-06 | 6.99E-07 | 6.99E-06 |
| Cadmium | 1.18E-05 | | 7.57E-06 | | 1.94E-05 | 1.17E-05 | | 7.51E-06 | | 1.92E-05 |
| Calcium | 1.74E-05 | 8.81E-08 | 6.96E-06 | 8.81E-07 | 2.54E-05 | 1.73E-05 | 8.74E-08 | 6.99E-06 | 8.74E-07 | 2.53E-05 |
| Chromium | 1.03E-02 | 2.29E-06 | 1.60E-03 | 1.73E-05 | 1.19E-02 | 1.02E-02 | 2.27E-06 | 1.59E-03 | 1.71E-05 | 1.19E-02 |
| Cobalt | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Copper | 2.02E+00 | 1.73E-05 | 3.44E-02 | 8.60E-05 | 2.05E+00 | 2.00E+00 | 1.72E-05 | 3.43E-02 | 8.54E-05 | 2.04E+00 |
| Gold | 5.28E-07 | | 2.64E-07 | | 7.93E-07 | 5.24E-07 | | 2.62E-07 | | 7.86E-07 |
| Iron | 1.84E+03 | | 5.92E+00 | 2.09E-01 | 1.84E+03 | 1.82E+03 | 3.31E-03 | 5.96E+00 | 2.07E-01 | 1.83E+03 |
| Lead | 8.10E+00 | 5.94E-05 | 1.47E-03 | 8.76E-05 | 8.10E+00 | 8.04E+00 | 5.89E-05 | 1.48E-03 | 8.69E-05 | 8.04E+00 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Lithium | 3.07E-02 | | | | 3.07E-02 | 3.04E-02 | | | | 3.04E-02 |
| Magnesium | 4.93E-03 | 2.99E-06 | 4.05E-03 | 2.03E-05 | 9.00E-03 | 4.89E-03 | 2.97E-06 | 4.02E-03 | 2.01E-05 | 8.93E-03 |
| Manganese | 1.54E+01 | 4.21E-05 | 6.41E-02 | 3.03E-04 | 1.55E+01 | 1.53E+01 | 4.18E-05 | 6.44E-02 | 3.01E-04 | 1.54E+01 |
| Molybdenum | 3.45E-03 | 1.76E-07 | 1.89E-04 | 1.50E-06 | 3.64E-03 | 3.42E-03 | 1.75E-07 | 1.88E-04 | 1.49E-06 | 3.61E-03 |
| Nickel | 5.38E-04 | 3.52E-07 | 3.35E-04 | 2.11E-06 | 8.76E-04 | 5.34E-04 | 3.50E-07 | 3.33E-04 | 2.10E-06 | 8.69E-04 |
| Phosphorus | 1.19E-02 | 1.03E-03 | 5.68E-04 | 1.12E-03 | 1.46E-02 | 1.18E-02 | 1.03E-03 | 5.65E-04 | 1.12E-03 | 1.45E-02 |
| Potassium | 1.67E-06 | | | | 1.67E-06 | 1.66E-06 | | | | 1.66E-06 |
| Silicon | 5.43E-03 | 3.17E-06 | 4.46E-03 | 2.18E-05 | 9.92E-03 | 5.39E-03 | 3.15E-06 | 4.43E-03 | 2.16E-05 | 9.84E-03 |
| Silver | 5.74E-03 | 8.81E-08 | 5.11E-06 | 8.81E-08 | 5.75E-03 | 5.70E-03 | 8.74E-08 | 5.07E-06 | 8.74E-08 | 5.70E-03 |
| Sulphur | 6.34E-02 | 9.62E-04 | 3.75E-02 | 1.21E-03 | 1.03E-01 | 6.29E-02 | 9.55E-04 | 3.73E-02 | 1.20E-03 | 1.02E-01 |
| Tantalum | 1.14E-06 | | 6.16E-07 | | 1.76E-06 | 1.14E-06 | | 6.12E-07 | | 1.75E-06 |
| Titanium | 5.07E-05 | | 1.14E-05 | 8.81E-08 | 6.23E-05 | 5.03E-05 | | 1.14E-05 | 8.74E-08 | 6.18E-05 |
| Vanadium | 2.00E-03 | | 4.45E-05 | | 2.04E-03 | 1.98E-03 | | 4.44E-05 | | 2.03E-03 |
| Zinc | 4.68E+00 | 3.96E-05 | 1.55E-03 | 6.21E-05 | 4.68E+00 | 4.65E+00 | 3.93E-05 | 1.55E-03 | 6.16E-05 | 4.65E+00 |
| **Non-renewable resources** | **2.06E+04** | **1.45E+00** | **1.06E+03** | **-1.46E+02** | **2.15E+04** | **2.05E+04** | **1.43E+00** | **1.06E+03** | **-1.45E+02** | **2.13E+04** |
| Basalt | 8.05E-02 | 8.81E-08 | 9.71E-04 | -2.76E-02 | 5.39E-02 | 7.99E-02 | 8.74E-08 | 9.73E-04 | -2.74E-02 | 5.35E-02 |
| Bauxite | 6.84E+01 | 1.98E-04 | 1.04E+00 | -3.73E-01 | 6.90E+01 | 6.78E+01 | 1.97E-04 | 1.04E+00 | -3.70E-01 | 6.85E+01 |
| Bentonite | 2.21E-01 | 6.51E-03 | 5.78E-02 | -8.15E-03 | 2.77E-01 | 2.19E-01 | 6.46E-03 | 5.87E-02 | -8.09E-03 | 2.76E-01 |
| Borax | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Chromium ore (39%) | 0.00E+00 | | | -1.16E-04 | -1.16E-04 | | | | -1.15E-04 | -1.15E-04 |
| Clay | -2.40E-02 | 8.30E-04 | 1.56E-01 | 1.14E+01 | 1.16E+01 | -2.38E-02 | 8.23E-04 | 1.55E-01 | 1.14E+01 | 1.15E+01 |
| Colemanite ore | 1.18E+01 | 8.81E-07 | 8.51E-01 | -1.29E-05 | 1.26E+01 | 1.17E+01 | 8.74E-07 | 8.48E-01 | -1.28E-05 | 1.25E+01 |
| Copper - Gold - Silver - ore (1.0% Cu; 0.4 | | | | -2.87E-02 | -2.87E-02 | | | | -2.84E-02 | -2.84E-02 |
| Copper - Gold - Silver - ore (1.1% Cu; 0.01 | | | | -1.75E-02 | -1.75E-02 | | | | -1.73E-02 | -1.73E-02 |
| Copper - Gold - Silver - ore (1.16% Cu; | | | | -9.86E-03 | -9.86E-03 | | | | -9.78E-03 | -9.78E-03 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Copper - Molybdenum - Gold - Silver - ore | | | | -2.71E-04 | -2.71E-04 | | | | -2.68E-04 | -2.68E-04 |
| Copper ore (0.14%) | | | | -4.33E-03 | -4.33E-03 | | | | -4.30E-03 | -4.30E-03 |
| Copper ore (1.2%) | | | | -2.97E-03 | -2.97E-03 | | | | -2.95E-03 | -2.95E-03 |
| Dolomite | 7.84E+00 | 3.15E-03 | 6.45E-01 | 4.14E-03 | 8.49E+00 | 7.78E+00 | 3.12E-03 | 6.43E-01 | 4.11E-03 | 8.43E+00 |
| Fluorspar (calcium fluoride; fluorite) | 1.40E+00 | 3.28E-04 | 8.39E-02 | -2.42E-03 | 1.48E+00 | 1.39E+00 | 3.25E-04 | 8.37E-02 | -2.40E-03 | 1.47E+00 |
| Graphite | 3.52E-07 | | 1.76E-07 | | 5.28E-07 | 3.50E-07 | | 1.75E-07 | | 5.24E-07 |
| Gypsum (natural gypsum) | -4.90E+00 | 2.12E-04 | -9.13E-03 | -8.72E-04 | -4.91E+00 | -4.86E+00 | 2.10E-04 | -9.25E-03 | -8.66E-04 | -4.87E+00 |
| Heavy spar (BaSO4) | 1.11E-02 | | 1.25E-04 | -4.13E-02 | -3.01E-02 | 1.11E-02 | | 1.26E-04 | -4.10E-02 | -2.98E-02 |
| Ilmenite (titanium ore) | 4.40E-02 | 6.16E-07 | 3.00E-03 | 2.38E-06 | 4.70E-02 | 4.37E-02 | 6.12E-07 | 2.99E-03 | 2.36E-06 | 4.67E-02 |
| Inert rock | 2.05E+04 | 1.18E+00 | 1.04E+03 | -1.79E+02 | 2.14E+04 | 2.04E+04 | 1.17E+00 | 1.04E+03 | -1.78E+02 | 2.12E+04 |
| Iron ore (56.86%) | | | | -1.65E-01 | -1.65E-01 | | | | -1.64E-01 | -1.64E-01 |
| Iron ore (65%) | | | | 4.57E-05 | 4.57E-05 | | | | 4.53E-05 | 4.53E-05 |
| Kaolin ore | 1.66E-04 | 5.28E-07 | 7.08E-05 | -2.71E-05 | 2.11E-04 | 1.65E-04 | 5.24E-07 | 7.05E-05 | -2.69E-05 | 2.09E-04 |
| Lead - Zinc - Silver - ore (5.49% Pb; 12.15% Zn; 57.4 gpt Ag) | | | | -8.07E-03 | -8.07E-03 | | | | -8.01E-03 | -8.01E-03 |
| Lead - zinc ore (4.6%-0.6%) | | | | -4.00E-02 | -4.00E-02 | | | | -3.97E-02 | -3.97E-02 |
| Limestone (calcium carbonate) | 4.80E+02 | 3.68E-02 | 7.47E+00 | -3.87E-02 | 4.88E+02 | 4.77E+02 | 3.66E-02 | 7.44E+00 | -3.84E-02 | 4.84E+02 |
| Magnesit (Magnesium carbonate) | 3.65E-02 | 6.15E-03 | 5.19E-03 | 6.67E-03 | 5.45E-02 | 3.62E-02 | 6.10E-03 | 5.16E-03 | 6.62E-03 | 5.41E-02 |
| Magnesite | 4.75E-05 | | 5.28E-07 | | 4.80E-05 | 4.71E-05 | 0.00E+00 | 5.24E-07 | 0.00E+00 | 4.76E-05 |
| Magnesium chloride leach (40%) | 3.62E-01 | 1.02E-04 | 1.07E-01 | 6.23E-01 | 1.09E+00 | 3.59E-01 | 1.01E-04 | 1.06E-01 | 6.19E-01 | 1.08E+00 |
| Manganese ore | | | | -2.30E-05 | -2.30E-05 | | | | -2.28E-05 | -2.28E-05 |
| Manganese ore (R.O.M.) | | | | -7.14E-05 | -7.14E-05 | | | | -7.09E-05 | -7.09E-05 |
| Molybdenite (Mo 0.24%) | | | | -1.66E-04 | -1.66E-04 | | | | -1.65E-04 | -1.65E-04 |
| Natural Aggregate | -5.48E+02 | 3.02E-03 | -7.47E-01 | 1.01E+01 | -5.39E+02 | -5.44E+02 | 3.00E-03 | -7.68E-01 | 1.00E+01 | -5.35E+02 |
| Natural pumice | 1.50E-02 | 6.16E-07 | 3.73E-04 | 2.64E-06 | 1.54E-02 | 1.49E-02 | 6.12E-07 | 3.71E-04 | 2.62E-06 | 1.53E-02 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Nickel ore (1.5%) | | | | -8.81E-08 | -8.81E-08 | | | | -8.74E-08 | -8.74E-08 |
| Nickel ore (1.6%) | | | | -2.10E-04 | -2.10E-04 | | | | -2.08E-04 | -2.08E-04 |
| Phonolite | 5.72E-06 | | 3.17E-06 | | 8.89E-06 | 5.68E-06 | 0.00E+00 | 3.15E-06 | | 8.82E-06 |
| Phosphate ore | -3.52E+00 | 2.83E-02 | 8.93E-01 | 3.33E-02 | -2.56E+00 | -3.49E+00 | 2.81E-02 | 8.87E-01 | 3.31E-02 | -2.54E+00 |
| Phosphorus minerals | | | | -8.81E-08 | -8.81E-08 | | | | -8.74E-08 | -8.74E-08 |
| Potashsalt, crude (hard salt, 10% K2O) | 6.02E-01 | 1.73E-01 | 1.26E+00 | 1.94E-01 | 2.23E+00 | 5.97E-01 | 1.72E-01 | 1.25E+00 | 1.93E-01 | 2.21E+00 |
| Potassium chloride | 4.84E-06 | | 8.81E-08 | | 4.93E-06 | 4.81E-06 | | 8.74E-08 | | 4.89E-06 |
| Precious metal ore (R.O.M) | | | | -7.49E-06 | -7.49E-06 | | | | -7.43E-06 | -7.43E-06 |
| Pyrite | 1.16E-03 | 1.76E-07 | 6.17E-05 | -1.76E-07 | 1.22E-03 | 1.15E-03 | 1.75E-07 | 6.17E-05 | -1.75E-07 | 1.22E-03 |
| Quartz sand (silica sand; silicon dioxide) | 9.05E+01 | 7.20E-04 | 3.35E+00 | 6.94E+00 | 1.01E+02 | 8.98E+01 | 7.14E-04 | 3.35E+00 | 6.89E+00 | 1.00E+02 |
| Sand | 3.14E-04 | | 3.35E-06 | | 3.17E-04 | 3.12E-04 | | 3.41E-06 | | 3.15E-04 |
| Shale | 1.19E-01 | 3.61E-06 | 1.58E-03 | 3.34E-05 | 1.21E-01 | 1.18E-01 | 3.58E-06 | 1.57E-03 | 3.31E-05 | 1.20E-01 |
| Sodium chloride (rock salt) | 5.43E+00 | 8.73E-04 | 1.20E-01 | 1.24E-01 | 5.68E+00 | 5.39E+00 | 8.66E-04 | 1.19E-01 | 1.23E-01 | 5.63E+00 |
| Soil | -1.47E+01 | 6.33E-03 | 4.52E+00 | 4.53E+00 | -5.63E+00 | -1.46E+01 | 6.28E-03 | 4.49E+00 | 4.49E+00 | -5.57E+00 |
| Stone from mountains | 1.83E-01 | 3.14E-05 | 4.18E-03 | 2.27E-03 | 1.90E-01 | 1.82E-01 | 3.12E-05 | 4.16E-03 | 2.25E-03 | 1.88E-01 |
| Sulphur (bonded) | 1.67E-06 | 2.64E-07 | 6.16E-07 | 2.64E-07 | 2.82E-06 | 1.66E-06 | 2.62E-07 | 6.12E-07 | 2.62E-07 | 2.80E-06 |
| Talc | 2.11E-06 | | 1.14E-06 | -5.28E-07 | 2.73E-06 | 2.10E-06 | | 1.14E-06 | -5.24E-07 | 2.71E-06 |
| Tin ore (0.01%) | 4.54E-04 | 2.64E-07 | 2.90E-04 | 1.50E-06 | 7.46E-04 | 4.51E-04 | 2.62E-07 | 2.88E-04 | 1.49E-06 | 7.40E-04 |
| Titanium ore | 2.94E-02 | | 5.72E-06 | -1.89E-04 | 2.92E-02 | 2.92E-02 | | 5.68E-06 | -1.88E-04 | 2.90E-02 |
| Zinc - copper ore (4.07%-2.59%) | | | | -1.01E-02 | -1.01E-02 | | | | -1.00E-02 | -1.00E-02 |
| Zinc - lead - copper ore (12%-3%-2%) | | | | -1.18E-02 | -1.18E-02 | | | | -1.17E-02 | -1.17E-02 |
| Zinc - Lead - Silver - Ore (7.5% Zn; 4.0% | | | | -8.29E-03 | -8.29E-03 | | | | -8.22E-03 | -8.22E-03 |
| **Renewable resources** | **2.44E+06** | **8.89E+02** | **4.13E+05** | **5.45E+03** | **2.85E+06** | **2.42E+06** | **8.82E+02** | **4.10E+05** | **5.42E+03** | **2.83E+06** |
| Water consumption | 2.43E+06 | 8.86E+02 | 4.12E+05 | 5.03E+03 | 2.84E+06 | 2.41E+06 | 8.79E+02 | 4.09E+05 | 5.00E+03 | 2.82E+06 |
| Air | 8.57E+03 | 2.50E+00 | 9.70E+02 | 4.24E+02 | 9.97E+03 | 8.51E+03 | 2.48E+00 | 9.63E+02 | 4.21E+02 | 9.89E+03 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Carbon dioxide | 5.97E+01 | 9.13E-01 | 3.40E+01 | -5.86E+00 | 8.88E+01 | 5.92E+01 | 9.06E-01 | 3.38E+01 | -5.82E+00 | 8.81E+01 |
| Forest, primary | 9.19E-05 | | 5.28E-07 | -1.43E-04 | -5.07E-05 | 9.12E-05 | | 5.24E-07 | -1.42E-04 | -5.03E-05 |
| Nitrogen | 3.20E-04 | | 3.43E-06 | 8.81E-08 | 3.23E-04 | 3.17E-04 | | 3.50E-06 | 8.74E-08 | 3.21E-04 |
| Oxygen | 1.04E+01 | 1.04E-04 | 8.78E-02 | 5.40E+00 | 1.59E+01 | 1.03E+01 | 1.03E-04 | 8.77E-02 | 5.35E+00 | 1.57E+01 |
| Renewable fuels | | | | 3.39E-05 | 3.39E-05 | | | | 3.36E-05 | 3.36E-05 |
| **Deposited goods** | **2.13E+04** | **1.06E+00** | **1.03E+03** | **9.15E+01** | **2.24E+04** | **2.11E+04** | **1.05E+00** | **1.03E+03** | **9.02E+01** | **2.23E+04** |
| **Hazardous waste** | **-1.76E-06** | | | | **-1.76E-06** | **-1.75E-06** | | | | **-1.75E-06** |
| Hazardous waste (underground deposit) | -1.76E-06 | | | | -1.76E-06 | -1.75E-06 | | | | -1.75E-06 |
| **Radioactive waste** | **-5.02E-01** | **-2.50E-04** | **-1.92E-01** | **9.01E-02** | **-6.04E-01** | **-4.98E-01** | **-2.48E-04** | **-1.90E-01** | **8.94E-02** | **-5.99E-01** |
| CaF2 (low radioactice) | | | | 5.16E-05 | 5.16E-05 | | | | 5.12E-05 | 5.12E-05 |
| High radioactive waste | -7.00E-04 | -3.52E-07 | -2.47E-04 | 1.52E-04 | -7.95E-04 | -6.94E-04 | -3.50E-07 | -2.45E-04 | 1.51E-04 | -7.89E-04 |
| Low radioactive wastes | -9.64E-03 | -4.76E-06 | -3.72E-03 | -3.16E-05 | -1.34E-02 | -9.57E-03 | -4.72E-06 | -3.69E-03 | -3.14E-05 | -1.33E-02 |
| Medium radioactive wastes | -4.69E-03 | -2.20E-06 | -1.82E-03 | 1.68E-04 | -6.35E-03 | -4.65E-03 | -2.18E-06 | -1.81E-03 | 1.66E-04 | -6.30E-03 |
| Plutonium as residual product | | | | 2.64E-07 | 2.64E-07 | | | | 2.62E-07 | 2.62E-07 |
| Radioactive tailings | -4.87E-01 | -2.43E-04 | -1.86E-01 | 8.88E-02 | -5.84E-01 | -4.83E-01 | -2.41E-04 | -1.84E-01 | 8.81E-02 | -5.80E-01 |
| Slag (Uranium conversion) | | | | 3.43E-04 | 3.43E-04 | | | | 3.40E-04 | 3.40E-04 |
| Uranium depleted | -5.05E-05 | | -5.28E-07 | 3.54E-04 | 3.03E-04 | -5.01E-05 | | -5.24E-07 | 3.51E-04 | 3.00E-04 |
| Waste radioactive | -4.37E-05 | | -4.40E-07 | 3.07E-04 | 2.62E-04 | -4.33E-05 | | -4.37E-07 | 3.04E-04 | 2.60E-04 |
| **Stockpile goods** | **2.13E+04** | **1.06E+00** | **1.03E+03** | **9.14E+01** | **2.24E+04** | **2.11E+04** | **1.05E+00** | **1.03E+03** | **9.01E+01** | **2.23E+04** |
| Demolition waste (deposited) | | | | -2.79E-01 | -2.79E-01 | | | | -2.77E-01 | -2.77E-01 |
| Hazardous waste (deposited) | 2.99E-05 | 1.15E-05 | 1.94E-06 | 1.25E-05 | 5.58E-05 | 2.96E-05 | 1.14E-05 | 1.92E-06 | 1.24E-05 | 5.54E-05 |
| Overburden (deposited) | 1.99E+04 | 1.03E+00 | 1.02E+03 | -1.79E+02 | 2.07E+04 | 1.97E+04 | 1.02E+00 | 1.02E+03 | -1.78E+02 | 2.06E+04 |
| Slag (deposited) | | | | 3.53E+01 | 3.53E+01 | 0.00E+00 | | | 3.50E+01 | 3.50E+01 |
| Slag (unspecified) | -3.55E+00 | | -3.83E-02 | | -3.59E+00 | -3.52E+00 | | -3.84E-02 | | -3.56E+00 |
| Spoil (deposited) | -1.19E+02 | 1.31E-02 | 1.69E+00 | 2.36E+00 | -1.15E+02 | -1.19E+02 | 1.30E-02 | 1.68E+00 | 2.34E+00 | -1.15E+02 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Tailings (deposited) | 1.40E+03 | 4.68E-03 | 7.93E+00 | 1.64E-02 | 1.41E+03 | 1.39E+03 | 4.64E-03 | 7.95E+00 | 1.63E-02 | 1.39E+03 |
| Treatment residue (mineral, deposited) | | | | 4.03E-02 | 4.03E-02 | | | | 4.00E-02 | 4.00E-02 |
| Waste (deposited) | 1.47E+02 | 1.36E-02 | 4.54E+00 | 2.33E+02 | 3.85E+02 | 1.46E+02 | 1.35E-02 | 4.52E+00 | 2.31E+02 | 3.82E+02 |
| **Emission to air** | **2.30E+04** | **2.88E+02** | **5.28E+03** | **8.32E+02** | **2.94E+04** | **2.28E+04** | **2.86E+02** | **5.24E+03** | **8.26E+02** | **2.92E+04** |
| **Heavy metal to air** | **8.65E-02** | **3.61E-06** | **4.55E-04** | **-8.22E-05** | **8.68E-02** | **8.57E-02** | **3.59E-06** | **4.57E-04** | **-8.15E-05** | **8.62E-02** |
| Antimony | 4.57E-05 | | 1.14E-06 | -7.04E-07 | 4.61E-05 | 4.53E-05 | | 1.14E-06 | -6.99E-07 | 4.58E-05 |
| Arsenic | 5.28E-07 | | | | 5.28E-07 | 5.24E-07 | | | | 5.24E-07 |
| Arsenic (+V) | 1.07E-04 | | 3.43E-06 | -2.82E-06 | 1.07E-04 | 1.06E-04 | | 3.41E-06 | -2.80E-06 | 1.06E-04 |
| Cadmium | 1.02E-04 | 2.64E-07 | 7.04E-07 | -1.76E-07 | 1.03E-04 | 1.01E-04 | 2.62E-07 | 6.99E-07 | -1.75E-07 | 1.02E-04 |
| Chromium | 2.05E-04 | 8.81E-08 | 4.58E-06 | -1.94E-06 | 2.08E-04 | 2.04E-04 | 8.74E-08 | 4.63E-06 | -1.92E-06 | 2.06E-04 |
| Chromium (+III) | 6.87E-06 | | 1.76E-07 | | 7.04E-06 | 6.82E-06 | | 1.75E-07 | | 6.99E-06 |
| Cobalt | 3.49E-05 | | 1.23E-06 | -5.28E-07 | 3.56E-05 | 3.46E-05 | | 1.31E-06 | -5.24E-07 | 3.54E-05 |
| Copper | 4.04E-04 | 8.81E-08 | 7.22E-06 | -2.55E-06 | 4.09E-04 | 4.01E-04 | 8.74E-08 | 7.25E-06 | -2.53E-06 | 4.06E-04 |
| Heavy metals to air (unspecified) | 1.94E-06 | | 4.40E-07 | | 2.38E-06 | 1.92E-06 | | 4.37E-07 | | 2.36E-06 |
| Iron | 7.11E-02 | 4.40E-07 | 2.39E-04 | 1.32E-06 | 7.13E-02 | 7.05E-02 | 4.37E-07 | 2.41E-04 | 1.31E-06 | 7.08E-02 |
| Lead | 4.87E-03 | 9.69E-07 | 3.13E-05 | 7.84E-06 | 4.91E-03 | 4.83E-03 | 9.61E-07 | 3.12E-05 | 7.78E-06 | 4.87E-03 |
| Manganese | 2.35E-03 | 8.81E-08 | 3.18E-05 | -6.87E-06 | 2.38E-03 | 2.34E-03 | 8.74E-08 | 3.16E-05 | -6.82E-06 | 2.36E-03 |
| Mercury | 1.10E-04 | | 4.23E-06 | 1.94E-06 | 1.17E-04 | 1.10E-04 | | 4.28E-06 | 1.92E-06 | 1.16E-04 |
| Molybdenum | 1.23E-06 | | 4.40E-07 | | 1.67E-06 | 1.22E-06 | | 4.37E-07 | | 1.66E-06 |
| Nickel | 6.26E-04 | 2.64E-07 | 1.16E-05 | -8.01E-06 | 6.30E-04 | 6.21E-04 | 2.62E-07 | 1.17E-05 | -7.95E-06 | 6.25E-04 |
| Selenium | 1.17E-04 | 8.81E-08 | 2.20E-05 | -2.31E-05 | 1.17E-04 | 1.17E-04 | 8.74E-08 | 2.18E-05 | -2.29E-05 | 1.16E-04 |
| Silver | 5.55E-06 | | 3.52E-06 | | 9.07E-06 | 5.50E-06 | | 3.50E-06 | | 9.00E-06 |
| Tellurium | -1.32E-06 | | | | -1.32E-06 | -1.31E-06 | | | | -1.31E-06 |
| Thallium | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Tin | 5.90E-04 | | 1.64E-05 | -9.07E-06 | 5.97E-04 | 5.85E-04 | | 1.63E-05 | -9.00E-06 | 5.93E-04 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Production** | **Setup** | **O&M** | **EoL** | **Total** | **Production** | **Setup** | **O&M** | **EoL** | **Total** |
| Titanium | 7.84E-05 | | 2.64E-07 | | 7.86E-05 | 7.78E-05 | | 2.62E-07 | | 7.80E-05 |
| Vanadium | 1.50E-03 | 1.14E-06 | 2.28E-05 | -1.37E-05 | 1.51E-03 | 1.49E-03 | 1.14E-06 | 2.32E-05 | -1.36E-05 | 1.50E-03 |
| Zinc | 4.20E-03 | 1.76E-07 | 5.23E-05 | -2.38E-05 | 4.23E-03 | 4.17E-03 | 1.75E-07 | 5.22E-05 | -2.36E-05 | 4.20E-03 |
| **Inorganic emission to air** | **1.88E+04** | **2.86E+02** | **4.16E+03** | **2.65E+02** | **2.35E+04** | **1.86E+04** | **2.84E+02** | **4.13E+03** | **2.63E+02** | **2.33E+04** |
| Aluminium | 5.55E-06 | 0.00E+00 | 3.52E-06 | | 9.07E-06 | 5.50E-06 | | 3.50E-06 | | 9.00E-06 |
| Ammonia | 2.15E-02 | 7.35E-04 | 5.11E-03 | 3.38E-03 | 3.08E-02 | 2.14E-02 | 7.30E-04 | 5.08E-03 | 3.35E-03 | 3.05E-02 |
| Ammonium | 8.81E-08 | | 1.76E-07 | | 2.64E-07 | 8.74E-08 | | 1.75E-07 | | 2.62E-07 |
| Argon | 2.04E-04 | 8.81E-08 | 1.24E-04 | 7.04E-07 | 3.29E-04 | 2.02E-04 | 8.74E-08 | 1.23E-04 | 6.99E-07 | 3.26E-04 |
| Barium | 7.51E-04 | 8.81E-08 | 3.13E-05 | -5.59E-05 | 7.27E-04 | 7.45E-04 | 8.74E-08 | 3.11E-05 | -5.55E-05 | 7.21E-04 |
| Beryllium | 6.16E-06 | | 1.76E-07 | -8.81E-08 | 6.25E-06 | 6.12E-06 | | 1.75E-07 | -8.74E-08 | 6.20E-06 |
| Boron | 1.88E-05 | | 1.76E-07 | | 1.90E-05 | 1.87E-05 | | 1.75E-07 | | 1.89E-05 |
| Boron compounds (unspecified) | 9.68E-04 | 4.40E-07 | 3.52E-04 | -1.87E-04 | 1.13E-03 | 9.60E-04 | 4.37E-07 | 3.50E-04 | -1.86E-04 | 1.12E-03 |
| Bromine | 2.49E-04 | 8.81E-08 | 6.89E-05 | -1.67E-04 | 1.51E-04 | 2.47E-04 | 8.74E-08 | 6.84E-05 | -1.65E-04 | 1.50E-04 |
| Carbon dioxide emissions | 4.63E+03 | 1.51E+01 | 3.15E+02 | 6.71E+01 | 5.03E+03 | 4.59E+03 | 1.50E+01 | 3.17E+02 | 6.65E+01 | 4.99E+03 |
| Carbon dioxide (aviation) | 8.59E-03 | 4.32E-06 | 5.34E-03 | 2.77E-05 | 1.40E-02 | 8.52E-03 | 4.28E-06 | 5.30E-03 | 2.75E-05 | 1.39E-02 |
| Carbon dioxide (biotic) | 7.32E+01 | 8.17E-01 | 3.38E+01 | 1.78E+00 | 1.10E+02 | 7.26E+01 | 8.10E-01 | 3.36E+01 | 1.77E+00 | 1.09E+02 |
| Carbon dioxide (land use change) | 1.39E+00 | 6.16E-02 | 3.92E-01 | 8.04E-02 | 1.92E+00 | 1.38E+00 | 6.11E-02 | 3.89E-01 | 7.98E-02 | 1.91E+00 |
| Carbon dioxide (peat oxidation) | 1.21E-04 | | 1.74E-05 | 8.81E-08 | 1.38E-04 | 1.20E-04 | | 1.73E-05 | 8.74E-08 | 1.37E-04 |
| Carbon monoxide | 3.69E+01 | 8.38E-03 | 3.31E-01 | 1.65E-04 | 3.73E+01 | 3.67E+01 | 8.31E-03 | 3.34E-01 | 1.64E-04 | 3.70E+01 |
| Chloride (unspecified) | 4.74E-03 | 5.28E-06 | 4.30E-04 | 6.25E-06 | 5.18E-03 | 4.70E-03 | 5.24E-06 | 4.31E-04 | 6.20E-06 | 5.14E-03 |
| Chlorine | 8.30E-04 | 8.81E-08 | 1.52E-05 | 5.28E-07 | 8.46E-04 | 8.24E-04 | 8.74E-08 | 1.51E-05 | 5.24E-07 | 8.39E-04 |
| Cyanide (unspecified) | 8.40E-05 | 8.81E-08 | 2.55E-06 | 8.81E-08 | 8.67E-05 | 8.34E-05 | 8.74E-08 | 2.62E-06 | 8.74E-08 | 8.62E-05 |
| Fluoride | 5.87E-02 | 4.40E-07 | 4.04E-03 | -6.37E-05 | 6.27E-02 | 5.83E-02 | 4.37E-07 | 4.03E-03 | -6.32E-05 | 6.23E-02 |
| Fluorine | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Helium | 1.76E-07 | | 8.81E-08 | -1.76E-07 | 8.81E-08 | 1.75E-07 | | 8.74E-08 | -1.75E-07 | 8.74E-08 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Hydrogen | 7.81E-03 | 1.33E-05 | 3.29E-04 | 4.22E-03 | 1.24E-02 | 7.75E-03 | 1.32E-05 | 3.28E-04 | 4.19E-03 | 1.23E-02 |
| Hydrogen bromide (hydrobromic acid) | 8.81E-08 | | | -8.81E-08 | | 8.74E-08 | | | -8.74E-08 | |
| Hydrogen chloride | 7.70E-02 | 1.40E-05 | 7.33E-03 | -1.72E-02 | 6.72E-02 | 7.64E-02 | 1.39E-05 | 7.28E-03 | -1.70E-02 | 6.67E-02 |
| Hydrogen cyanide (prussic acid) | 1.97E-05 | | 8.81E-08 | | 1.98E-05 | 1.96E-05 | | 8.74E-08 | | 1.97E-05 |
| Hydrogen fluoride | 1.08E-02 | 1.06E-06 | 5.06E-04 | -1.49E-03 | 9.81E-03 | 1.07E-02 | 1.05E-06 | 5.03E-04 | -1.48E-03 | 9.74E-03 |
| Hydrogen phosphorous | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Hydrogen sulphide | 5.71E-02 | 3.27E-05 | 1.54E-02 | -4.26E-04 | 7.22E-02 | 5.67E-02 | 3.24E-05 | 1.53E-02 | -4.22E-04 | 7.16E-02 |
| Nitrogen (atmospheric nitrogen) | 2.98E+00 | 6.57E-03 | 1.86E-02 | 1.77E-02 | 3.02E+00 | 2.95E+00 | 6.52E-03 | 1.86E-02 | 1.75E-02 | 3.00E+00 |
| Nitrogen (N-compounds) | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | 0.00E+00 | | | 8.74E-08 |
| Nitrogen dioxide | 3.14E-01 | 1.37E-03 | 2.01E-02 | 1.43E-03 | 3.36E-01 | 3.11E-01 | 1.36E-03 | 2.00E-02 | 1.42E-03 | 3.34E-01 |
| Nitrogen monoxide | 7.87E-03 | 3.61E-03 | 1.94E-03 | 3.93E-03 | 1.73E-02 | 7.81E-03 | 3.58E-03 | 1.93E-03 | 3.90E-03 | 1.72E-02 |
| Nitrogen oxides | 7.03E+00 | 1.95E-02 | 4.00E+00 | -1.00E-01 | 1.09E+01 | 6.98E+00 | 1.94E-02 | 4.08E+00 | -9.95E-02 | 1.10E+01 |
| Nitrogen, total | 2.64E-07 | | | | 2.64E-07 | 2.62E-07 | | | | 2.62E-07 |
| Nitrous oxide (laughing gas) | 4.10E-02 | 8.65E-04 | 1.39E-02 | -5.34E-04 | 5.53E-02 | 4.07E-02 | 8.59E-04 | 1.40E-02 | -5.29E-04 | 5.51E-02 |
| Oxygen | 5.62E+00 | 2.41E-03 | 2.53E+00 | 1.56E-01 | 8.31E+00 | 5.58E+00 | 2.39E-03 | 2.52E+00 | 1.55E-01 | 8.25E+00 |
| Sulphate | 1.23E-03 | | 1.33E-05 | | 1.24E-03 | 1.22E-03 | | 1.33E-05 | | 1.23E-03 |
| Sulphur | 7.04E-07 | | 2.64E-07 | | 9.69E-07 | 6.99E-07 | | 2.62E-07 | | 9.61E-07 |
| Sulphur dioxide | 7.66E+00 | 1.27E-02 | 2.30E+00 | -3.23E-01 | 9.65E+00 | 7.60E+00 | 1.26E-02 | 2.35E+00 | -3.20E-01 | 9.64E+00 |
| Sulphur trioxide | 2.41E-03 | 8.81E-07 | 4.77E-05 | 5.28E-07 | 2.46E-03 | 2.39E-03 | 8.74E-07 | 4.74E-05 | 5.24E-07 | 2.44E-03 |
| Sulphuric acid | 1.67E-06 | | 2.64E-07 | 1.22E-05 | 1.41E-05 | 1.66E-06 | | 2.62E-07 | 1.21E-05 | 1.40E-05 |
| Water (evapotranspiration) | 7.41E+03 | 2.68E+02 | 3.11E+03 | 3.01E+02 | 1.11E+04 | 7.35E+03 | 2.66E+02 | 3.08E+03 | 2.99E+02 | 1.10E+04 |
| Water vapour | 6.58E+03 | 1.73E+00 | 6.91E+02 | -1.05E+02 | 7.16E+03 | 6.52E+03 | 1.72E+00 | 6.87E+02 | -1.04E+02 | 7.11E+03 |
| Zinc sulphate | 5.28E-07 | | | | 5.28E-07 | 5.24E-07 | | | | 5.24E-07 |
| **Organic emission to air (group VOC)** | **4.42E+00** | **2.40E-02** | **6.16E-01** | **-1.02E-01** | **4.96E+00** | **4.39E+00** | **2.37E-02** | **6.23E-01** | **-1.01E-01** | **4.93E+00** |
| Group PAH to air | 8.86E-04 | 1.59E-06 | 1.36E-05 | -2.82E-06 | 8.98E-04 | 8.79E-04 | 1.57E-06 | 1.35E-05 | -2.80E-06 | 8.91E-04 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Halogenated organic emissions to air | 9.18E-04 | | 1.28E-05 | -2.18E-05 | 9.09E-04 | 9.10E-04 | | 1.28E-05 | -2.16E-05 | 9.02E-04 |
| 1-Butylene (Vinylacetylene) | 6.16E-07 | | | | 6.16E-07 | 6.12E-07 | | | | 6.12E-07 |
| 1-Methoxy-2-propanol | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| 1-Pentene | 2.29E-06 | | | | 2.29E-06 | 2.27E-06 | | | | 2.27E-06 |
| 2,2,4-Trimethylpentane | 4.40E-07 | | | | 4.40E-07 | 4.37E-07 | | | | 4.37E-07 |
| 2,2-Dimethylbutane | 4.40E-07 | | | | 4.40E-07 | 4.37E-07 | | | | 4.37E-07 |
| 2,4-Dimethylpentane | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| 2-Methyl-1-butene | 1.67E-06 | | | | 1.67E-06 | 1.66E-06 | | | | 1.66E-06 |
| 2-Methylpentane | 3.08E-06 | | | | 3.08E-06 | 3.06E-06 | | | | 3.06E-06 |
| 3-Methylpentane | 1.50E-06 | | | | 1.50E-06 | 1.49E-06 | | | | 1.49E-06 |
| Acetaldehyde (Ethanal) | 2.96E-04 | 8.81E-08 | 6.69E-06 | -4.05E-06 | 2.99E-04 | 2.94E-04 | 8.74E-08 | 6.64E-06 | -4.02E-06 | 2.97E-04 |
| Acetic acid | 1.25E-03 | 4.40E-07 | 7.79E-05 | -3.68E-05 | 1.29E-03 | 1.24E-03 | 4.37E-07 | 7.75E-05 | -3.65E-05 | 1.28E-03 |
| Acetone (dimethyl ketone) | 3.85E-04 | 8.81E-08 | 6.60E-06 | -3.79E-06 | 3.88E-04 | 3.82E-04 | 8.74E-08 | 6.55E-06 | -3.76E-06 | 3.85E-04 |
| Acrolein | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Acrylonitrile | 1.67E-06 | | | | 1.67E-06 | 1.66E-06 | | | | 1.66E-06 |
| Aldehyde (unspecified) | 2.20E-06 | | 7.93E-07 | -1.84E-05 | -1.54E-05 | 2.18E-06 | 0.00E+00 | 7.86E-07 | -1.83E-05 | -1.53E-05 |
| Alkane (unspecified) | 3.27E-03 | 1.14E-06 | 3.59E-04 | -3.13E-04 | 3.31E-03 | 3.24E-03 | 1.14E-06 | 3.56E-04 | -3.11E-04 | 3.29E-03 |
| Alkene (unspecified) | 2.15E-03 | 8.81E-07 | 3.35E-04 | -3.01E-04 | 2.18E-03 | 2.13E-03 | 8.74E-07 | 3.33E-04 | -2.99E-04 | 2.17E-03 |
| Benzene | 1.01E-03 | 2.62E-05 | 2.09E-04 | -3.99E-05 | 1.21E-03 | 1.01E-03 | 2.60E-05 | 2.09E-04 | -3.96E-05 | 1.20E-03 |
| Butane (n-butane) | 9.31E-03 | 3.54E-04 | 4.50E-03 | 2.28E-04 | 1.44E-02 | 9.24E-03 | 3.52E-04 | 4.59E-03 | 2.26E-04 | 1.44E-02 |
| cis-2-Pentene | 1.76E-06 | | | | 1.76E-06 | 1.75E-06 | | | | 1.75E-06 |
| Cyclohexane (hexahydro benzene) | 6.08E-06 | | | | 6.08E-06 | 6.03E-06 | | | | 6.03E-06 |
| Cyclopentane | 2.64E-07 | | | | 2.64E-07 | 2.62E-07 | | | | 2.62E-07 |
| Ethane | 2.68E-02 | 9.49E-04 | 1.19E-02 | -1.23E-03 | 3.84E-02 | 2.66E-02 | 9.42E-04 | 1.22E-02 | -1.22E-03 | 3.84E-02 |
| Ethanol | 5.91E-04 | 1.76E-07 | 1.30E-05 | -8.45E-06 | 5.95E-04 | 5.86E-04 | 1.75E-07 | 1.30E-05 | -8.39E-06 | 5.91E-04 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Ethene (ethylene) | 6.36E-04 | | 4.65E-05 | -2.64E-07 | 6.82E-04 | 6.31E-04 | | 4.64E-05 | -2.62E-07 | 6.77E-04 |
| Ethyl benzene | 2.18E-03 | 8.81E-07 | 3.34E-04 | -3.01E-04 | 2.22E-03 | 2.16E-03 | 8.74E-07 | 3.32E-04 | -2.99E-04 | 2.20E-03 |
| Fluorene | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Formaldehyde (methanal) | 2.27E-03 | 7.56E-05 | 4.88E-04 | -1.87E-04 | 2.64E-03 | 2.25E-03 | 7.50E-05 | 4.84E-04 | -1.85E-04 | 2.62E-03 |
| Heptane (isomers) | 2.79E-04 | 1.25E-05 | 1.40E-04 | 1.31E-05 | 4.45E-04 | 2.77E-04 | 1.24E-05 | 1.43E-04 | 1.30E-05 | 4.46E-04 |
| Hexane (isomers) | 7.24E-04 | 8.44E-05 | 2.32E-04 | 9.07E-05 | 1.13E-03 | 7.19E-04 | 8.37E-05 | 2.36E-04 | 9.00E-05 | 1.13E-03 |
| Hydrocarbons, aromatic | 1.17E-04 | | 2.47E-06 | -1.23E-06 | 1.18E-04 | 1.16E-04 | | 2.45E-06 | -1.22E-06 | 1.17E-04 |
| iso-Butane | 3.50E-05 | | 3.52E-07 | -6.50E-04 | -6.15E-04 | 3.48E-05 | | 3.50E-07 | -6.45E-04 | -6.10E-04 |
| iso-Pentane | 3.40E-05 | | 3.52E-07 | | 3.43E-05 | 3.37E-05 | | 3.50E-07 | | 3.41E-05 |
| Isopropanol | 5.55E-06 | | 3.43E-06 | | 8.98E-06 | 5.50E-06 | | 3.41E-06 | | 8.91E-06 |
| Mercaptan (unspecified) | 1.88E-05 | | 1.76E-07 | -7.93E-07 | 1.82E-05 | 1.87E-05 | | 1.75E-07 | -7.86E-07 | 1.81E-05 |
| Methanol | 2.25E-02 | 4.59E-05 | 6.49E-04 | 4.01E-05 | 2.32E-02 | 2.23E-02 | 4.55E-05 | 6.53E-04 | 3.98E-05 | 2.30E-02 |
| Methyl cyclopentane | 6.16E-07 | | | | 6.16E-07 | 6.12E-07 | | | | 6.12E-07 |
| Methyl tert-butylether | 1.67E-06 | | | | 1.67E-06 | 1.66E-06 | | | | 1.66E-06 |
| NMVOC (unspecified) | 3.53E-01 | 1.80E-03 | 1.50E-01 | 2.66E-03 | 5.07E-01 | 3.50E-01 | 1.78E-03 | 1.53E-01 | 2.64E-03 | 5.08E-01 |
| Octane | 1.53E-04 | 6.87E-06 | 7.71E-05 | 7.22E-06 | 2.44E-04 | 1.52E-04 | 6.82E-06 | 7.89E-05 | 7.16E-06 | 2.44E-04 |
| Pentane (n-pentane) | 5.01E-03 | 1.20E-04 | 2.14E-03 | -6.11E-04 | 6.67E-03 | 4.97E-03 | 1.19E-04 | 2.17E-03 | -6.06E-04 | 6.65E-03 |
| Phenol (hydroxy benzene) | 5.02E-05 | 1.20E-05 | 6.16E-07 | 1.22E-05 | 7.49E-05 | 4.98E-05 | 1.19E-05 | 6.12E-07 | 1.21E-05 | 7.44E-05 |
| Propane | 4.24E-02 | 1.72E-03 | 2.00E-02 | 2.60E-04 | 6.44E-02 | 4.21E-02 | 1.71E-03 | 2.05E-02 | 2.59E-04 | 6.45E-02 |
| Propene (propylene) | 2.17E-04 | 5.28E-07 | 3.50E-05 | -2.67E-05 | 2.26E-04 | 2.15E-04 | 5.24E-07 | 3.49E-05 | -2.65E-05 | 2.24E-04 |
| Propionic acid (propane acid) | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Propylene glycol methyl ether acetate | 8.81E-07 | | 5.28E-07 | | 1.41E-06 | 8.74E-07 | | 5.24E-07 | | 1.40E-06 |
| Styrene | 4.24E-05 | 1.01E-05 | 4.40E-07 | 1.03E-05 | 6.32E-05 | 4.20E-05 | 1.00E-05 | 4.37E-07 | 1.02E-05 | 6.27E-05 |
| Toluene (methyl benzene) | 1.43E-03 | 1.38E-05 | 1.55E-04 | -1.20E-04 | 1.48E-03 | 1.42E-03 | 1.37E-05 | 1.54E-04 | -1.19E-04 | 1.47E-03 |
| trans-2-Butene | 1.32E-06 | | | | 1.32E-06 | 1.31E-06 | | | | 1.31E-06 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| trans-2-Pentene | 3.26E-06 | | | | 3.26E-06 | 3.23E-06 | | | | 3.23E-06 |
| Xylene (dimethyl benzene) | 9.35E-03 | 8.10E-06 | 1.40E-03 | -1.25E-03 | 9.51E-03 | 9.27E-03 | 8.04E-06 | 1.39E-03 | -1.24E-03 | 9.44E-03 |
| Xylene (meta-Xylene; 1,3- | 4.40E-07 | | | | 4.40E-07 | 4.37E-07 | | | | 4.37E-07 |
| Hydrocarbons (unspecified) | 1.38E-01 | 4.58E-06 | 1.29E-03 | 1.22E-05 | 1.40E-01 | 1.37E-01 | 4.54E-06 | 1.30E-03 | 1.21E-05 | 1.39E-01 |
| Methane | 3.69E+00 | 1.75E-02 | 3.87E-01 | -1.02E-01 | 3.99E+00 | 3.66E+00 | 1.73E-02 | 3.90E-01 | -1.01E-01 | 3.96E+00 |
| Methane (biotic) | 1.08E-01 | 1.25E-03 | 3.47E-02 | 1.47E-03 | 1.45E-01 | 1.07E-01 | 1.24E-03 | 3.44E-02 | 1.46E-03 | 1.44E-01 |
| VOC (unspecified) | 2.52E-04 | | 2.73E-06 | 1.18E-04 | 3.73E-04 | 2.50E-04 | | 2.71E-06 | 1.18E-04 | 3.70E-04 |
| **Other emission to air** | **4.27E+03** | **2.16E+00** | **1.12E+03** | **5.68E+02** | **5.96E+03** | **4.23E+03** | **2.15E+00** | **1.12E+03** | **5.63E+02** | **5.91E+03** |
| Acid (as H+) | 2.51E-05 | | 2.64E-07 | | 2.54E-05 | 2.49E-05 | | 2.62E-07 | | 2.52E-05 |
| Clean gas | 1.04E+01 | 2.01E-03 | 6.07E-02 | 7.82E-01 | 1.12E+01 | 1.03E+01 | 2.00E-03 | 6.01E-02 | 7.76E-01 | 1.11E+01 |
| Exhaust | 2.22E+03 | 1.79E+00 | 7.53E+02 | 5.52E+02 | 3.53E+03 | 2.20E+03 | 1.78E+00 | 7.48E+02 | 5.48E+02 | 3.50E+03 |
| Total organic carbon | 1.21E+00 | | 1.56E-02 | | 1.23E+00 | 1.20E+00 | | 1.55E-02 | | 1.22E+00 |
| Unused primary energy from solar energy | 5.84E+02 | 2.91E-01 | 3.61E+02 | 1.93E+00 | 9.47E+02 | 5.79E+02 | 2.89E-01 | 3.58E+02 | 1.92E+00 | 9.40E+02 |
| Used air | 1.45E+03 | 8.06E-02 | 9.32E+00 | 1.28E+01 | 1.47E+03 | 1.44E+03 | 7.99E-02 | 9.31E+00 | 1.27E+01 | 1.46E+03 |
| **Particles to air** | **2.69E+00** | **2.15E-03** | **3.38E-01** | **-9.79E-03** | **3.02E+00** | **2.67E+00** | **2.14E-03** | **3.45E-01** | **-9.72E-03** | **3.00E+00** |
| Dust (> PM10) | 1.33E+00 | 2.35E-05 | 1.83E-02 | 1.14E-03 | 1.35E+00 | 1.32E+00 | 2.33E-05 | 1.83E-02 | 1.13E-03 | 1.34E+00 |
| Dust (PM10) | 5.39E-01 | 9.69E-07 | 1.80E-03 | -5.46E-03 | 5.35E-01 | 5.35E-01 | 9.61E-07 | 1.81E-03 | -5.42E-03 | 5.31E-01 |
| Dust (PM2.5 - PM10) | 6.16E-01 | 2.13E-04 | 9.01E-03 | 1.09E-03 | 6.27E-01 | 6.12E-01 | 2.11E-04 | 9.04E-03 | 1.08E-03 | 6.22E-01 |
| Dust (PM2.5) | 1.99E-01 | 1.91E-03 | 3.09E-01 | -6.56E-03 | 5.03E-01 | 1.97E-01 | 1.90E-03 | 3.16E-01 | -6.51E-03 | 5.09E-01 |
| Metals (unspecified) | 2.08E-03 | | 7.35E-05 | | 2.15E-03 | 2.06E-03 | 0.00E+00 | 7.34E-05 | | 2.13E-03 |
| **Pesticides to air** | **8.02E-06** | | **4.76E-06** | | **1.28E-05** | **7.94E-06** | | **4.72E-06** | | **1.27E-05** |
| Atrazine | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | 0.00E+00 | | 8.74E-08 |
| Benomyl | 2.64E-07 | | 1.76E-07 | | 4.40E-07 | 2.62E-07 | | 1.75E-07 | | 4.37E-07 |
| Glyphosate | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Mancozeb | 4.23E-06 | | 2.73E-06 | | 6.96E-06 | 4.19E-06 | | 2.71E-06 | | 6.90E-06 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Trifluralin | 3.26E-06 | | 1.85E-06 | | 5.11E-06 | 3.23E-06 | | 1.83E-06 | | 5.07E-06 |
| **Emission to fresh water** | **5.68E+05** | **2.67E+02** | **3.17E+05** | **-6.82E+03** | **8.78E+05** | **5.64E+05** | **2.65E+02** | **3.14E+05** | **-6.76E+03** | **8.72E+05** |
| **Analytical measures to fresh water** | **7.77E-01** | **9.82E-04** | **2.15E-01** | **-5.60E-03** | **9.88E-01** | **7.70E-01** | **9.74E-04** | **2.14E-01** | **-5.57E-03** | **9.80E-01** |
| Adsorbable organic halogen compounds | 1.30E-03 | 6.16E-07 | 1.10E-04 | 1.34E-03 | 2.75E-03 | 1.29E-03 | 6.12E-07 | 1.09E-04 | 1.33E-03 | 2.73E-03 |
| Biological oxygen demand (BOD) | 3.70E-02 | 2.18E-05 | 9.27E-04 | -7.49E-06 | 3.80E-02 | 3.67E-02 | 2.16E-05 | 9.28E-04 | -7.43E-06 | 3.77E-02 |
| Chemical oxygen demand (COD) | 7.06E-01 | 9.13E-04 | 2.13E-01 | -6.36E-03 | 9.14E-01 | 7.00E-01 | 9.05E-04 | 2.12E-01 | -6.32E-03 | 9.07E-01 |
| Nitrogenous Matter (unspecified, as N) | 1.70E-02 | 8.81E-08 | 5.82E-05 | 5.28E-07 | 1.70E-02 | 1.68E-02 | 8.74E-08 | 5.85E-05 | 5.24E-07 | 1.69E-02 |
| Solids (dissolved) | 1.19E-03 | -8.81E-08 | 3.97E-04 | -5.74E-04 | 1.01E-03 | 1.18E-03 | -8.74E-08 | 3.94E-04 | -5.69E-04 | 1.00E-03 |
| Total dissolved organic bound carbon | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Total organic bound carbon (TOC) | 1.44E-02 | 4.69E-05 | 8.06E-04 | -2.38E-06 | 1.52E-02 | 1.42E-02 | 4.66E-05 | 8.23E-04 | -2.36E-06 | 1.51E-02 |
| **Heavy metal to fresh water** | **4.18E-01** | **1.61E-04** | **1.15E-01** | **-2.01E-02** | **5.13E-01** | **4.15E-01** | **1.60E-04** | **1.14E-01** | **-2.00E-02** | **5.09E-01** |
| Antimony | 1.94E-06 | | 8.81E-08 | 8.81E-08 | 2.11E-06 | 1.92E-06 | | 8.74E-08 | 8.74E-08 | 2.10E-06 |
| Arsenic (+V) | 4.66E-04 | 1.13E-05 | 1.06E-04 | 1.22E-05 | 5.96E-04 | 4.62E-04 | 1.12E-05 | 1.08E-04 | 1.21E-05 | 5.94E-04 |
| Cadmium | 2.04E-04 | 4.84E-06 | 4.26E-05 | 4.32E-06 | 2.56E-04 | 2.03E-04 | 4.81E-06 | 4.36E-05 | 4.28E-06 | 2.55E-04 |
| Chromium | 6.68E-04 | 1.77E-05 | 1.59E-04 | 1.88E-05 | 8.63E-04 | 6.63E-04 | 1.76E-05 | 1.62E-04 | 1.87E-05 | 8.61E-04 |
| Chromium (+III) | 2.53E-05 | 4.40E-07 | 7.04E-06 | -4.40E-07 | 3.23E-05 | 2.51E-05 | 4.37E-07 | 6.99E-06 | -4.37E-07 | 3.21E-05 |
| Chromium (+VI) | 2.69E-05 | | 5.28E-07 | | 2.74E-05 | 2.66E-05 | | 5.24E-07 | | 2.72E-05 |
| Cobalt | 1.94E-06 | | | | 1.94E-06 | 1.92E-06 | | | | 1.92E-06 |
| Copper | 2.92E-04 | 4.32E-06 | 4.51E-05 | 1.85E-06 | 3.43E-04 | 2.89E-04 | 4.28E-06 | 4.58E-05 | 1.83E-06 | 3.41E-04 |
| Iron | 4.12E-01 | 1.08E-04 | 1.14E-01 | -2.01E-02 | 5.06E-01 | 4.09E-01 | 1.07E-04 | 1.13E-01 | -2.00E-02 | 5.02E-01 |
| Lead | 5.19E-04 | 5.11E-06 | 6.54E-05 | -1.59E-06 | 5.88E-04 | 5.15E-04 | 5.07E-06 | 6.58E-05 | -1.57E-06 | 5.84E-04 |
| Manganese | 1.62E-03 | 8.81E-08 | 8.80E-05 | -4.62E-05 | 1.67E-03 | 1.61E-03 | 8.74E-08 | 8.74E-05 | -4.59E-05 | 1.65E-03 |
| Mercury | 5.02E-06 | | 7.04E-07 | | 5.72E-06 | 4.98E-06 | 0.00E+00 | 6.99E-07 | 0.00E+00 | 5.68E-06 |
| Molybdenum | 8.78E-05 | 8.81E-08 | 3.11E-05 | -8.89E-06 | 1.10E-04 | 8.71E-05 | 8.74E-08 | 3.09E-05 | -8.82E-06 | 1.09E-04 |
| Nickel | 5.15E-04 | 8.01E-06 | 8.43E-05 | 7.31E-06 | 6.14E-04 | 5.11E-04 | 7.95E-06 | 8.53E-05 | 7.25E-06 | 6.11E-04 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Selenium | 1.90E-05 | | 4.49E-06 | -1.50E-06 | 2.20E-05 | 1.89E-05 | | 4.46E-06 | -1.49E-06 | 2.18E-05 |
| Silver | 3.61E-06 | | 8.81E-08 | 0.00E+00 | 3.70E-06 | 3.58E-06 | | 8.74E-08 | | 3.67E-06 |
| Titanium | 7.56E-05 | | 8.37E-06 | -9.69E-07 | 8.30E-05 | 7.51E-05 | | 8.30E-06 | -9.61E-07 | 8.24E-05 |
| Tungsten | 8.81E-08 | | 8.81E-08 | | 1.76E-07 | 8.74E-08 | | 8.74E-08 | | 1.75E-07 |
| Vanadium | 2.32E-05 | | 5.99E-06 | -2.82E-06 | 2.64E-05 | 2.31E-05 | | 5.94E-06 | -2.80E-06 | 2.62E-05 |
| Zinc | 1.94E-03 | 1.14E-06 | 3.29E-05 | -2.20E-06 | 1.97E-03 | 1.92E-03 | 1.14E-06 | 3.29E-05 | -2.18E-06 | 1.95E-03 |
| **Inorganic emission to fresh water** | **2.92E+01** | **5.01E-01** | **5.86E+00** | **1.42E-01** | **3.57E+01** | **2.89E+01** | **4.97E-01** | **5.95E+00** | **1.41E-01** | **3.55E+01** |
| Acid (calculated as H+) | 8.52E-03 | | 1.19E-04 | -7.48E-05 | 8.56E-03 | 8.45E-03 | | 1.19E-04 | -7.42E-05 | 8.50E-03 |
| Aluminium | 3.04E-03 | 9.69E-07 | 6.32E-04 | -2.76E-04 | 3.40E-03 | 3.02E-03 | 9.61E-07 | 6.28E-04 | -2.74E-04 | 3.37E-03 |
| Ammonia | 1.01E-03 | 7.04E-07 | 2.62E-04 | 2.47E-06 | 1.28E-03 | 1.01E-03 | 6.99E-07 | 2.60E-04 | 2.45E-06 | 1.27E-03 |
| Ammonium / ammonia | 1.41E-02 | 4.67E-06 | 3.72E-04 | -6.70E-05 | 1.44E-02 | 1.39E-02 | 4.63E-06 | 3.69E-04 | -6.65E-05 | 1.43E-02 |
| Barium | 3.57E-03 | 9.78E-05 | 8.51E-04 | 1.13E-04 | 4.64E-03 | 3.55E-03 | 9.71E-05 | 8.70E-04 | 1.12E-04 | 4.63E-03 |
| Beryllium | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Boron | 1.08E-03 | 3.52E-07 | 4.72E-04 | -4.75E-05 | 1.50E-03 | 1.07E-03 | 3.50E-07 | 4.68E-04 | -4.71E-05 | 1.49E-03 |
| Calcium | 3.46E-01 | 8.22E-05 | 7.68E-02 | -6.42E-03 | 4.16E-01 | 3.43E-01 | 8.15E-05 | 7.62E-02 | -6.37E-03 | 4.13E-01 |
| Carbon disulphide | 8.81E-08 | | 8.81E-08 | | 1.76E-07 | 8.74E-08 | | 8.74E-08 | | 1.75E-07 |
| Carbonate | 2.19E-01 | 6.31E-03 | 5.35E-02 | 7.31E-03 | 2.86E-01 | 2.17E-01 | 6.26E-03 | 5.47E-02 | 7.25E-03 | 2.85E-01 |
| Chlorate | 6.16E-07 | | | | 6.16E-07 | 6.12E-07 | | | | 6.12E-07 |
| Chloride | 2.59E+01 | 4.88E-01 | 4.97E+00 | 2.56E-01 | 3.16E+01 | 2.57E+01 | 4.84E-01 | 5.06E+00 | 2.54E-01 | 3.15E+01 |
| Chlorine | 3.09E-04 | | 3.35E-06 | | 3.13E-04 | 3.07E-04 | | 3.32E-06 | | 3.10E-04 |
| Chlorine (dissolved) | 2.27E-03 | 1.23E-06 | 8.56E-04 | -4.13E-04 | 2.72E-03 | 2.26E-03 | 1.22E-06 | 8.50E-04 | -4.10E-04 | 2.70E-03 |
| Cyanide | 4.81E-05 | | 7.04E-07 | 3.52E-07 | 4.91E-05 | 4.77E-05 | | 6.99E-07 | 3.50E-07 | 4.88E-05 |
| Fluoride | 3.07E-01 | 1.31E-04 | 1.60E-01 | -2.19E-02 | 4.46E-01 | 3.05E-01 | 1.30E-04 | 1.59E-01 | -2.18E-02 | 4.42E-01 |
| Fluorine | 3.79E-06 | | 1.76E-07 | -1.76E-07 | 3.79E-06 | 3.76E-06 | | 1.75E-07 | -1.75E-07 | 3.76E-06 |
| Hydrogen chloride | 4.68E-03 | | 3.43E-06 | | 4.69E-03 | 4.65E-03 | | 3.41E-06 | | 4.65E-03 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Hydrogen fluoride (hydrofluoric acid) | 7.04E-06 | | 1.76E-07 | 1.29E-05 | 2.01E-05 | 6.99E-06 | | 1.75E-07 | 1.28E-05 | 1.99E-05 |
| Hydrogen peroxide | 5.90E-04 | 2.64E-07 | 3.62E-04 | 1.94E-06 | 9.55E-04 | 5.86E-04 | 2.62E-07 | 3.60E-04 | 1.92E-06 | 9.48E-04 |
| Hydroxide | 9.69E-07 | | 4.40E-07 | -2.29E-04 | -2.28E-04 | 9.61E-07 | | 4.37E-07 | -2.28E-04 | -2.26E-04 |
| Magnesium | 3.21E-02 | 1.47E-05 | 1.44E-02 | 8.33E-05 | 4.65E-02 | 3.18E-02 | 1.46E-05 | 1.43E-02 | 8.27E-05 | 4.62E-02 |
| Magnesium chloride | 2.38E-06 | | 1.59E-06 | | 3.96E-06 | 2.36E-06 | | 1.57E-06 | | 3.93E-06 |
| Metal ions (unspecific) | 6.34E-06 | | 3.61E-06 | | 9.95E-06 | 6.29E-06 | | 3.58E-06 | | 9.87E-06 |
| Nitrate | 1.18E-01 | 8.18E-04 | 3.85E-02 | 3.17E-04 | 1.58E-01 | 1.17E-01 | 8.11E-04 | 3.82E-02 | 3.15E-04 | 1.57E-01 |
| Nitrite | 7.04E-07 | | | | 7.04E-07 | 6.99E-07 | | | | 6.99E-07 |
| Nitrogen | 7.31E-03 | 5.28E-07 | 6.63E-05 | 8.81E-07 | 7.38E-03 | 7.26E-03 | 5.24E-07 | 6.61E-05 | 8.74E-07 | 7.32E-03 |
| Nitrogen (as total N) | 5.90E-06 | | 2.29E-06 | | 8.19E-06 | 5.85E-06 | | 2.27E-06 | | 8.13E-06 |
| Nitrogen organic bound | 2.44E-02 | 5.83E-04 | 7.46E-03 | 6.80E-04 | 3.31E-02 | 2.42E-02 | 5.78E-04 | 7.42E-03 | 6.75E-04 | 3.29E-02 |
| Phosphate | 4.96E-03 | 1.41E-04 | 1.74E-03 | 1.62E-04 | 7.00E-03 | 4.92E-03 | 1.40E-04 | 1.73E-03 | 1.61E-04 | 6.95E-03 |
| Phosphorus | 5.16E-03 | 2.47E-06 | 1.48E-04 | 1.14E-06 | 5.32E-03 | 5.12E-03 | 2.45E-06 | 1.47E-04 | 1.14E-06 | 5.28E-03 |
| Potassium | 9.73E-03 | 2.03E-04 | 3.90E-04 | 2.22E-04 | 1.05E-02 | 9.66E-03 | 2.01E-04 | 3.88E-04 | 2.20E-04 | 1.05E-02 |
| Silicate particles | 5.28E-07 | | 8.81E-08 | | 6.16E-07 | 5.24E-07 | | 8.74E-08 | | 6.12E-07 |
| Sodium | 4.51E-01 | 4.28E-04 | 1.14E-01 | -2.29E-02 | 5.43E-01 | 4.48E-01 | 4.24E-04 | 1.14E-01 | -2.27E-02 | 5.39E-01 |
| Sodium chloride (rock salt) | 1.97E-04 | 1.76E-07 | 1.24E-04 | 1.06E-06 | 3.23E-04 | 1.96E-04 | 1.75E-07 | 1.23E-04 | 1.05E-06 | 3.20E-04 |
| Sodium hypochlorite | 1.53E-02 | 7.04E-07 | 2.82E-04 | 5.55E-06 | 1.55E-02 | 1.51E-02 | 6.99E-07 | 2.80E-04 | 5.50E-06 | 1.54E-02 |
| Sodium sulphate | 1.42E-02 | 6.96E-06 | 8.68E-03 | 4.56E-05 | 2.29E-02 | 1.41E-02 | 6.90E-06 | 8.62E-03 | 4.53E-05 | 2.27E-02 |
| Strontium | 6.45E-03 | 2.20E-06 | 1.48E-04 | -6.56E-05 | 6.53E-03 | 6.40E-03 | 2.18E-06 | 1.48E-04 | -6.51E-05 | 6.48E-03 |
| Sulfate | 1.61E+00 | 3.40E-03 | 4.01E-01 | -7.19E-02 | 1.95E+00 | 1.60E+00 | 3.37E-03 | 3.99E-01 | -7.13E-02 | 1.93E+00 |
| Sulphide | 4.10E-02 | 1.12E-03 | 9.74E-03 | 1.30E-03 | 5.32E-02 | 4.07E-02 | 1.11E-03 | 9.96E-03 | 1.29E-03 | 5.31E-02 |
| Sulphite | 3.17E-04 | 8.81E-08 | 1.43E-04 | -1.44E-05 | 4.45E-04 | 3.14E-04 | 8.74E-08 | 1.42E-04 | -1.42E-05 | 4.42E-04 |
| Sulphur | 6.28E-05 | | 7.04E-07 | | 6.35E-05 | 6.23E-05 | | 6.99E-07 | | 6.30E-05 |
| Sulphur trioxide | 4.93E-06 | | 3.08E-06 | | 8.01E-06 | 4.89E-06 | | 3.06E-06 | | 7.95E-06 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Sulphuric acid | 1.67E-06 | | 1.06E-06 | -2.64E-07 | 2.47E-06 | 1.66E-06 | | 1.05E-06 | -2.62E-07 | 2.45E-06 |
| **Organic emission to fresh water** | **6.40E-01** | **9.09E-03** | **1.14E-01** | **1.08E-02** | **7.74E-01** | **6.36E-01** | **9.02E-03** | **1.14E-01** | **1.07E-02** | **7.68E-01** |
| **Halogenated organic emissions to fresh** | **1.15E-05** | | **8.81E-08** | | **1.16E-05** | **1.14E-05** | | **8.74E-08** | | **1.15E-05** |
| Pentachlorophenol (PCP) | 1.11E-05 | | 8.81E-08 | | 1.12E-05 | 1.10E-05 | | 8.74E-08 | | 1.11E-05 |
| Tetrachloroethene (perchloroethylene) | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Trichloromethane (chloroform) | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| **Hydrocarbons to fresh water** | **6.40E-01** | **9.09E-03** | **1.14E-01** | **1.08E-02** | **7.74E-01** | **6.36E-01** | **9.02E-03** | **1.14E-01** | **1.07E-02** | **7.68E-01** |
| Acenaphthene | 6.16E-07 | | 1.76E-07 | | 7.93E-07 | 6.12E-07 | | 1.75E-07 | | 7.86E-07 |
| Acenaphthylene | 2.64E-07 | | 8.81E-08 | | 3.52E-07 | 2.62E-07 | | 8.74E-08 | | 3.50E-07 |
| Acetic acid | 3.61E-06 | | 2.20E-06 | 7.04E-07 | 6.52E-06 | 3.58E-06 | | 2.18E-06 | 6.99E-07 | 6.47E-06 |
| Anthracene | 1.06E-06 | | 2.64E-07 | | 1.32E-06 | 1.05E-06 | | 2.62E-07 | | 1.31E-06 |
| Aromatic hydrocarbons (unspecified) | 1.05E-05 | 1.76E-07 | 1.59E-06 | -2.64E-07 | 1.20E-05 | 1.04E-05 | 1.75E-07 | 1.66E-06 | -2.62E-07 | 1.20E-05 |
| Benzene | 1.34E-03 | 3.67E-05 | 3.19E-04 | 4.24E-05 | 1.74E-03 | 1.33E-03 | 3.64E-05 | 3.26E-04 | 4.21E-05 | 1.73E-03 |
| Benzo{a}anthracene | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Chrysene | 2.64E-07 | | 8.81E-08 | | 3.52E-07 | 2.62E-07 | | 8.74E-08 | | 3.50E-07 |
| Ethyl benzene | 7.29E-05 | 2.03E-06 | 1.73E-05 | 2.29E-06 | 9.46E-05 | 7.23E-05 | 2.01E-06 | 1.77E-05 | 2.27E-06 | 9.44E-05 |
| Fluoranthene | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Hydrocarbons (unspecified) | 3.84E-05 | | 7.04E-06 | -3.96E-06 | 4.15E-05 | 3.81E-05 | | 6.99E-06 | -3.93E-06 | 4.12E-05 |
| Methanol | 2.57E-03 | 4.32E-06 | 2.03E-04 | 9.48E-05 | 2.87E-03 | 2.55E-03 | 4.28E-06 | 2.02E-04 | 9.40E-05 | 2.85E-03 |
| Naphthalene | 4.21E-05 | 1.14E-06 | 1.00E-05 | 1.32E-06 | 5.46E-05 | 4.18E-05 | 1.14E-06 | 1.02E-05 | 1.31E-06 | 5.44E-05 |
| Oil (unspecified) | 3.28E-01 | 1.97E-04 | 4.68E-03 | 2.43E-04 | 3.33E-01 | 3.26E-01 | 1.96E-04 | 4.76E-03 | 2.41E-04 | 3.31E-01 |
| Phenol (hydroxy benzene) | 1.40E-03 | 3.72E-05 | 3.27E-04 | 4.32E-05 | 1.80E-03 | 1.39E-03 | 3.69E-05 | 3.34E-04 | 4.29E-05 | 1.80E-03 |
| Polycyclic aromatic hydrocarbons (PAH, | 1.05E-05 | | 1.76E-07 | -4.14E-06 | 6.52E-06 | 1.04E-05 | | 1.75E-07 | -4.11E-06 | 6.47E-06 |
| Toluene (methyl benzene) | 8.16E-04 | 2.24E-05 | 1.94E-04 | 2.59E-05 | 1.06E-03 | 8.10E-04 | 2.22E-05 | 1.98E-04 | 2.57E-05 | 1.06E-03 |
| VOC (unspecified) | 7.04E-07 | | | | 7.04E-07 | 6.99E-07 | | | | 6.99E-07 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Xylene (isomers; dimethyl benzene) | 2.91E-04 | 8.01E-06 | 6.93E-05 | 8.98E-06 | 3.78E-04 | 2.89E-04 | 7.95E-06 | 7.08E-05 | 8.91E-06 | 3.77E-04 |
| Carbon, organically bound | 2.65E-01 | 8.78E-03 | 1.07E-01 | 1.03E-02 | 3.91E-01 | 2.63E-01 | 8.71E-03 | 1.07E-01 | 1.02E-02 | 3.88E-01 |
| Organic compounds (dissolved) | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Organic compounds (unspecified) | 4.08E-02 | 1.32E-06 | 7.85E-04 | 1.44E-05 | 4.16E-02 | 4.05E-02 | 1.31E-06 | 7.81E-04 | 1.43E-05 | 4.13E-02 |
| **Other emission to fresh water** | **5.68E+05** | **2.67E+02** | **3.17E+05** | **-6.82E+03** | **8.78E+05** | **5.64E+05** | **2.65E+02** | **3.14E+05** | **-6.76E+03** | **8.72E+05** |
| **Pesticides to fresh water** | **5.30E+05** | **2.49E+02** | **3.04E+05** | **1.92E+03** | **8.35E+05** | **5.26E+05** | **2.47E+02** | **3.01E+05** | **1.91E+03** | **8.29E+05** |
| Alachlor | 7.84E-06 | | 5.20E-06 | | 1.30E-05 | 7.78E-06 | | 5.16E-06 | | 1.29E-05 |
| Mancozeb | 2.64E-07 | | 1.76E-07 | | 4.40E-07 | 2.62E-07 | | 1.75E-07 | | 4.37E-07 |
| Trifluralin | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Collected rainwater to river | 1.11E+02 | 1.07E-02 | 2.91E+00 | 1.66E+02 | 2.80E+02 | 1.10E+02 | 1.06E-02 | 2.91E+00 | 1.65E+02 | 2.78E+02 |
| Cooling water to river | 2.88E+02 | 2.70E+00 | 2.56E+01 | 2.88E+01 | 3.45E+02 | 2.86E+02 | 2.68E+00 | 2.61E+01 | 2.86E+01 | 3.43E+02 |
| Cooling water to river, regionalized, DE | 4.45E+03 | 6.73E+00 | 8.77E+03 | 3.85E+01 | 1.33E+04 | 4.41E+03 | 6.68E+00 | 8.70E+03 | 3.82E+01 | 1.32E+04 |
| Processed water to groundwater | 5.20E+01 | 1.80E-03 | 2.70E+00 | 5.05E+01 | 1.05E+02 | 5.16E+01 | 1.79E-03 | 2.68E+00 | 5.01E+01 | 1.04E+02 |
| Processed water to river | 4.87E+03 | 5.93E+00 | 1.37E+02 | 1.67E+01 | 5.03E+03 | 4.83E+03 | 5.88E+00 | 1.38E+02 | 1.65E+01 | 4.99E+03 |
| Processed water to river, regionalized, DE | 3.00E+03 | 2.86E-01 | 3.87E+02 | 2.57E+00 | 3.39E+03 | 2.97E+03 | 2.84E-01 | 3.84E+02 | 2.55E+00 | 3.36E+03 |
| Turbined water to river | 9.81E+04 | 9.63E+00 | 1.53E+03 | 3.41E+02 | 1.00E+05 | 9.74E+04 | 9.55E+00 | 1.53E+03 | 3.39E+02 | 9.92E+04 |
| Turbined water to river, regionalized, DE | 4.19E+05 | 2.24E+02 | 2.93E+05 | 1.28E+03 | 7.13E+05 | 4.16E+05 | 2.22E+02 | 2.90E+05 | 1.27E+03 | 7.08E+05 |
| **Particles to fresh water** | **3.76E+00** | **9.86E-02** | **1.19E+00** | **7.16E-02** | **5.12E+00** | **3.73E+00** | **9.79E-02** | **1.18E+00** | **7.08E-02** | **5.09E+00** |
| Dust (> PM10) | 4.65E-02 | | 5.02E-04 | | 4.70E-02 | 4.62E-02 | | 5.03E-04 | | 4.67E-02 |
| Dust (PM10) | 6.87E-06 | | 8.81E-08 | | 6.96E-06 | 6.82E-06 | | 8.74E-08 | | 6.90E-06 |
| Soil loss by erosion into water | 2.58E+00 | 8.59E-02 | 1.05E+00 | 1.01E-01 | 3.82E+00 | 2.56E+00 | 8.53E-02 | 1.04E+00 | 1.00E-01 | 3.79E+00 |
| Solids (suspended) | 1.13E+00 | 1.27E-02 | 1.37E-01 | -2.94E-02 | 1.25E+00 | 1.12E+00 | 1.26E-02 | 1.39E-01 | -2.92E-02 | 1.25E+00 |
| **Radioactive emissions to fresh water** | **3.79E+04** | **1.75E+01** | **1.34E+04** | **-8.74E+03** | **4.26E+04** | **3.76E+04** | **1.74E+01** | **1.33E+04** | **-8.67E+03** | **4.23E+04** |
| Radium (Ra226) | 3.79E+04 | 1.75E+01 | 1.34E+04 | -8.74E+03 | 4.26E+04 | 3.76E+04 | 1.74E+01 | 1.33E+04 | -8.67E+03 | 4.23E+04 |
| **Emissions to sea water** | **2.58E+03** | **1.22E+00** | **4.88E+02** | **1.44E+01** | **3.09E+03** | **2.56E+03** | **1.21E+00** | **4.85E+02** | **1.43E+01** | **3.06E+03** |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| **Analytical measures to sea water** | **5.26E-03** | **1.63E-04** | **1.67E-03** | **1.17E-04** | **7.22E-03** | **5.22E-03** | **1.62E-04** | **1.71E-03** | **1.16E-04** | **7.21E-03** |
| Biological oxygen demand (BOD) | 9.00E-05 | 2.03E-06 | 1.95E-05 | -1.94E-06 | 1.10E-04 | 8.93E-05 | 2.01E-06 | 1.98E-05 | -1.92E-06 | 1.09E-04 |
| Chemical oxygen demand (COD) | 5.08E-03 | 1.59E-04 | 1.63E-03 | 1.21E-04 | 7.00E-03 | 5.04E-03 | 1.58E-04 | 1.67E-03 | 1.20E-04 | 6.99E-03 |
| Nitrogenous Matter (unspecified, as N) | 5.28E-07 | | 2.64E-07 | | 7.93E-07 | 5.24E-07 | 0.00E+00 | 2.62E-07 | 0.00E+00 | 7.86E-07 |
| Total organic bound carbon (TOC) | 9.00E-05 | 2.03E-06 | 1.95E-05 | -1.94E-06 | 1.10E-04 | 8.93E-05 | 2.01E-06 | 1.98E-05 | -1.92E-06 | 1.09E-04 |
| **Heavy metals to sea water** | **4.18E-04** | **1.37E-05** | **1.42E-04** | **1.06E-05** | **5.85E-04** | **4.15E-04** | **1.36E-05** | **1.45E-04** | **1.05E-05** | **5.85E-04** |
| Arsenic (+V) | 9.91E-05 | 3.26E-06 | 3.41E-05 | 3.61E-06 | 1.40E-04 | 9.83E-05 | 3.23E-06 | 3.49E-05 | 3.58E-06 | 1.40E-04 |
| Cadmium | 4.24E-05 | 1.41E-06 | 1.46E-05 | 1.41E-06 | 5.98E-05 | 4.20E-05 | 1.40E-06 | 1.49E-05 | 1.40E-06 | 5.98E-05 |
| Chromium | 1.55E-04 | 5.20E-06 | 5.34E-05 | 4.67E-06 | 2.19E-04 | 1.54E-04 | 5.16E-06 | 5.46E-05 | 4.63E-06 | 2.19E-04 |
| Cobalt | 8.81E-08 | | | -8.81E-08 | | 8.74E-08 | | | -8.74E-08 | |
| Copper | 3.34E-05 | 1.06E-06 | 1.08E-05 | 6.16E-07 | 4.59E-05 | 3.31E-05 | 1.05E-06 | 1.10E-05 | 6.12E-07 | 4.58E-05 |
| Iron | 9.69E-07 | | | -8.81E-07 | 8.81E-08 | 9.61E-07 | | | -8.74E-07 | 8.74E-08 |
| Lead | 2.93E-05 | 9.69E-07 | 9.95E-06 | 9.69E-07 | 4.12E-05 | 2.91E-05 | 9.61E-07 | 1.01E-05 | 9.61E-07 | 4.12E-05 |
| Manganese | 8.81E-08 | | | -8.81E-08 | | 8.74E-08 | | | -8.74E-08 | |
| Mercury | 2.64E-07 | | 8.81E-08 | | 3.52E-07 | 2.62E-07 | 0.00E+00 | 8.74E-08 | 0.00E+00 | 3.50E-07 |
| Nickel | 5.48E-05 | 1.85E-06 | 1.87E-05 | 1.94E-06 | 7.72E-05 | 5.43E-05 | 1.83E-06 | 1.91E-05 | 1.92E-06 | 7.72E-05 |
| Vanadium | 8.81E-08 | | | -8.81E-08 | | 8.74E-08 | | | -8.74E-08 | |
| Zinc | 2.47E-06 | | 2.64E-07 | -1.50E-06 | 1.23E-06 | 2.45E-06 | | 2.62E-07 | -1.49E-06 | 1.22E-06 |
| **Inorganic emissions to sea water** | 4.39E+00 | 1.46E-01 | 1.51E+00 | 1.48E-01 | 6.20E+00 | 4.36E+00 | 1.45E-01 | 1.54E+00 | 1.47E-01 | 6.20E+00 |
| Aluminium | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Ammonia | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Ammonium / ammonia | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Barium | 8.66E-04 | 2.88E-05 | 2.98E-04 | 2.91E-05 | 1.22E-03 | 8.59E-04 | 2.86E-05 | 3.04E-04 | 2.89E-05 | 1.22E-03 |
| Boron | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Calcium | 6.25E-06 | 0.00E+00 | 8.81E-08 | -1.76E-07 | 6.16E-06 | 6.20E-06 | | 8.74E-08 | -1.75E-07 | 6.12E-06 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Carbonate | 5.45E-02 | 1.81E-03 | 1.87E-02 | 1.84E-03 | 7.68E-02 | 5.41E-02 | 1.80E-03 | 1.91E-02 | 1.82E-03 | 7.68E-02 |
| Chloride | 4.30E+00 | 1.43E-01 | 1.48E+00 | 1.45E-01 | 6.07E+00 | 4.27E+00 | 1.42E-01 | 1.51E+00 | 1.44E-01 | 6.07E+00 |
| Fluoride | 2.53E-03 | | 3.60E-05 | | 2.57E-03 | 2.51E-03 | | 3.59E-05 | | 2.55E-03 |
| Magnesium | 1.72E-05 | 3.52E-07 | 3.43E-06 | -3.52E-07 | 2.06E-05 | 1.70E-05 | 3.50E-07 | 3.50E-06 | -3.50E-07 | 2.05E-05 |
| Nitrate | 4.51E-04 | 2.47E-06 | 1.08E-04 | 4.05E-06 | 5.65E-04 | 4.48E-04 | 2.45E-06 | 1.08E-04 | 4.02E-06 | 5.62E-04 |
| Nitrite | 5.46E-06 | 0.00E+00 | 1.23E-06 | | 6.69E-06 | 5.42E-06 | | 1.22E-06 | 0.00E+00 | 6.64E-06 |
| Phosphorus | 8.81E-08 | 0.00E+00 | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Sodium | 1.80E-03 | 4.02E-05 | 3.90E-04 | -3.88E-05 | 2.19E-03 | 1.78E-03 | 3.98E-05 | 3.95E-04 | -3.85E-05 | 2.18E-03 |
| Strontium | 2.55E-06 | | 4.40E-07 | -8.81E-08 | 2.91E-06 | 2.53E-06 | | 4.37E-07 | -8.74E-08 | 2.88E-06 |
| Sulphate | 2.30E-02 | 7.62E-04 | 7.88E-03 | 7.55E-04 | 3.24E-02 | 2.28E-02 | 7.56E-04 | 8.06E-03 | 7.49E-04 | 3.23E-02 |
| Sulphide | 9.92E-03 | 3.29E-04 | 3.41E-03 | 3.38E-04 | 1.40E-02 | 9.84E-03 | 3.27E-04 | 3.48E-03 | 3.36E-04 | 1.40E-02 |
| Sulphur | 1.23E-06 | | 2.64E-07 | | 1.50E-06 | 1.22E-06 | | 2.62E-07 | 0.00E+00 | 1.49E-06 |
| **Organic emissions to sea water** | **2.61E-03** | **8.65E-05** | **8.95E-04** | **8.73E-05** | **3.68E-03** | **2.59E-03** | **8.58E-05** | **9.15E-04** | **8.67E-05** | **3.68E-03** |
| **Hydrocarbons to sea water** | **2.61E-03** | **8.65E-05** | **8.95E-04** | **8.73E-05** | **3.68E-03** | **2.59E-03** | **8.58E-05** | **9.15E-04** | **8.67E-05** | **3.68E-03** |
| Acenaphthene | 1.76E-07 | | 8.81E-08 | | 2.64E-07 | 1.75E-07 | | 8.74E-08 | | 2.62E-07 |
| Acenaphthylene | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Anthracene | 2.64E-07 | | 8.81E-08 | | 3.52E-07 | 2.62E-07 | | 8.74E-08 | | 3.50E-07 |
| Aromatic hydrocarbons (unspecified) | 8.81E-07 | | 1.76E-07 | | 1.06E-06 | 8.74E-07 | | 1.75E-07 | | 1.05E-06 |
| Benzene | 3.25E-04 | 1.08E-05 | 1.12E-04 | 1.08E-05 | 4.58E-04 | 3.22E-04 | 1.07E-05 | 1.14E-04 | 1.07E-05 | 4.58E-04 |
| Chrysene | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Ethyl benzene | 1.78E-05 | 6.16E-07 | 6.08E-06 | 2.64E-07 | 2.47E-05 | 1.76E-05 | 6.12E-07 | 6.20E-06 | 2.62E-07 | 2.47E-05 |
| Hydrocarbons (unspecified) | 7.13E-06 | 0.00E+00 | 8.81E-08 | | 7.22E-06 | 7.08E-06 | | 8.74E-08 | | 7.16E-06 |
| Oil (unspecified) | 1.65E-03 | 5.49E-05 | 5.68E-04 | 5.66E-05 | 2.33E-03 | 1.64E-03 | 5.44E-05 | 5.81E-04 | 5.62E-05 | 2.33E-03 |
| Phenol (hydroxy benzene) | 3.29E-04 | 1.09E-05 | 1.13E-04 | 1.07E-05 | 4.63E-04 | 3.26E-04 | 1.08E-05 | 1.15E-04 | 1.07E-05 | 4.63E-04 |
| Toluene (methyl benzene) | 1.97E-04 | 6.60E-06 | 6.79E-05 | 6.34E-06 | 2.78E-04 | 1.96E-04 | 6.55E-06 | 6.95E-05 | 6.29E-06 | 2.78E-04 |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| Xylene (isomers; dimethyl benzene) | 7.08E-05 | 2.38E-06 | 2.43E-05 | 2.20E-06 | 9.97E-05 | 7.03E-05 | 2.36E-06 | 2.48E-05 | 2.18E-06 | 9.96E-05 |
| Naphthalene | 1.03E-05 | 3.52E-07 | 3.52E-06 | 3.52E-07 | 1.45E-05 | 1.02E-05 | 3.50E-07 | 3.58E-06 | 3.50E-07 | 1.45E-05 |
| **Other emissions to sea water** | **2.58E+03** | **1.07E+00** | **4.87E+02** | **1.43E+01** | **3.08E+03** | **2.56E+03** | **1.06E+00** | **4.84E+02** | **1.42E+01** | **3.05E+03** |
| Cooling water to sea | 2.56E+03 | 1.03E+00 | 4.86E+02 | 1.42E+01 | 3.06E+03 | 2.54E+03 | 1.02E+00 | 4.83E+02 | 1.41E+01 | 3.03E+03 |
| Processed water to sea | 1.86E+01 | 3.89E-02 | 6.84E-01 | 6.34E-02 | 1.94E+01 | 1.84E+01 | 3.86E-02 | 6.91E-01 | 6.29E-02 | 1.92E+01 |
| **Particles to sea water** | **7.16E-02** | **1.60E-03** | **1.55E-02** | **-1.55E-03** | **8.72E-02** | **7.11E-02** | **1.59E-03** | **1.57E-02** | **-1.54E-03** | **8.68E-02** |
| Dust (> PM10) | 1.52E-03 | | 1.64E-05 | | 1.54E-03 | 1.51E-03 | | 1.65E-05 | | 1.53E-03 |
| Solids (suspended) | 7.01E-02 | 1.60E-03 | 1.55E-02 | -1.55E-03 | 8.57E-02 | 6.96E-02 | 1.59E-03 | 1.57E-02 | -1.54E-03 | 8.53E-02 |
| **Emissions to agricultural soil** | **7.28E-05** | **2.64E-05** | **8.11E-06** | **2.83E-05** | **1.36E-04** | **7.23E-05** | **2.62E-05** | **8.04E-06** | **2.81E-05** | **1.35E-04** |
| **Heavy metals to agricultural soil** | **7.23E-05** | **2.64E-05** | **8.11E-06** | **2.83E-05** | **1.35E-04** | **7.18E-05** | **2.62E-05** | **8.04E-06** | **2.81E-05** | **1.34E-04** |
| Cadmium | 4.40E-06 | 1.76E-07 | 2.03E-06 | 1.76E-07 | 6.78E-06 | 4.37E-06 | 1.75E-07 | 2.01E-06 | 1.75E-07 | 6.73E-06 |
| Chromium | -1.59E-06 | | -3.52E-07 | | -1.94E-06 | -1.57E-06 | | -3.50E-07 | | -1.92E-06 |
| Chromium (+III) | 1.46E-05 | 3.35E-06 | 1.94E-06 | 3.70E-06 | 2.36E-05 | 1.45E-05 | 3.32E-06 | 1.92E-06 | 3.67E-06 | 2.34E-05 |
| Copper | 6.52E-06 | 3.26E-06 | 6.16E-07 | 3.52E-06 | 1.39E-05 | 6.47E-06 | 3.23E-06 | 6.12E-07 | 3.50E-06 | 1.38E-05 |
| Iron | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Lead | 2.01E-05 | 4.93E-06 | 2.29E-06 | 5.28E-06 | 3.26E-05 | 1.99E-05 | 4.89E-06 | 2.27E-06 | 5.24E-06 | 3.23E-05 |
| Mercury | 1.76E-07 | | | | 1.76E-07 | 1.75E-07 | | | | 1.75E-07 |
| Nickel | 5.46E-06 | 1.67E-06 | 5.28E-07 | 1.76E-06 | 9.42E-06 | 5.42E-06 | 1.66E-06 | 5.24E-07 | 1.75E-06 | 9.35E-06 |
| Tin | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Zinc | 2.25E-05 | 1.30E-05 | 1.06E-06 | 1.39E-05 | 5.05E-05 | 2.24E-05 | 1.29E-05 | 1.05E-06 | 1.38E-05 | 5.02E-05 |
| **Inorganic emissions to agricultural soil** | **4.40E-07** | | | | **4.40E-07** | **4.37E-07** | | | | **4.37E-07** |
| Aluminium | 2.64E-07 | | | | 2.64E-07 | 2.62E-07 | | | | 2.62E-07 |
| Chlorine | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| Sulphur | 8.81E-08 | | | | 8.81E-08 | 8.74E-08 | | | | 8.74E-08 |
| **Emissions to industrial soil** | **6.45E-02** | **1.94E-06** | **1.63E-03** | **1.80E-02** | **8.43E-02** | **6.41E-02** | **1.93E-06** | **1.62E-03** | **1.79E-02** | **8.35E-02** |

| Flow | Baseline | | | | | Yaw control | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Production | Setup | O&M | EoL | Total | Production | Setup | O&M | EoL | Total |
| **Heavy metals to industrial soil** | **1.71E-03** | | **1.81E-05** | **1.36E-03** | **3.09E-03** | **1.69E-03** | | **1.83E-05** | **1.35E-03** | **3.07E-03** |
| Arsenic (+V) | 8.33E-04 | | 8.98E-06 | 2.64E-07 | 8.42E-04 | 8.26E-04 | | 9.00E-06 | 2.62E-07 | 8.35E-04 |
| Chromium | 1.76E-07 | | | -9.69E-07 | -7.93E-07 | 1.75E-07 | | | -9.61E-07 | -7.86E-07 |
| Iron | 8.74E-04 | | 9.16E-06 | 1.36E-03 | 2.24E-03 | 8.67E-04 | | 9.26E-06 | 1.35E-03 | 2.23E-03 |
| Manganese | 2.64E-07 | | | 4.40E-07 | 7.04E-07 | 2.62E-07 | | | 4.37E-07 | 6.99E-07 |
| Nickel | 1.76E-07 | | | 8.81E-07 | 1.06E-06 | 1.75E-07 | | | 8.74E-07 | 1.05E-06 |
| Zinc | 8.81E-08 | | | 3.79E-06 | 3.87E-06 | 8.74E-08 | | | 3.76E-06 | 3.84E-06 |
| **Inorganic emissions to industrial soil** | **6.28E-02** | **1.94E-06** | **1.61E-03** | **1.71E-02** | **8.16E-02** | **6.24E-02** | **1.93E-06** | **1.60E-03** | **1.70E-02** | **8.08E-02** |
| Aluminium | 5.90E-06 | | 8.81E-08 | 1.89E-03 | 1.90E-03 | 5.85E-06 | | 8.74E-08 | 1.88E-03 | 1.88E-03 |
| Ammonia | 6.83E-03 | 2.64E-07 | 3.28E-05 | -6.05E-04 | 6.26E-03 | 6.78E-03 | 2.62E-07 | 3.29E-05 | -6.00E-04 | 6.21E-03 |
| Calcium | 5.83E-03 | 1.76E-07 | 2.77E-05 | -1.49E-05 | 5.85E-03 | 5.79E-03 | 1.75E-07 | 2.77E-05 | -1.48E-05 | 5.80E-03 |
| Chloride | 1.17E-02 | 1.50E-06 | 1.18E-03 | 1.65E-02 | 2.94E-02 | 1.16E-02 | 1.49E-06 | 1.17E-03 | 1.64E-02 | 2.91E-02 |
| Fluoride | 6.56E-05 | | 1.50E-06 | 1.53E-05 | 8.24E-05 | 6.51E-05 | | 1.49E-06 | 1.52E-05 | 8.18E-05 |
| Magnesium | 5.80E-04 | | 2.82E-06 | -2.11E-06 | 5.81E-04 | 5.75E-04 | | 2.80E-06 | -2.10E-06 | 5.76E-04 |
| Phosphorus | 3.70E-03 | | 1.29E-05 | -6.20E-05 | 3.65E-03 | 3.67E-03 | | 1.28E-05 | -6.15E-05 | 3.62E-03 |
| Potassium | 1.17E-03 | | 6.08E-06 | -1.54E-04 | 1.02E-03 | 1.16E-03 | | 6.03E-06 | -1.53E-04 | 1.01E-03 |
| Sodium | 2.66E-04 | | 2.64E-06 | -1.23E-06 | 2.67E-04 | 2.64E-04 | | 2.71E-06 | -1.22E-06 | 2.65E-04 |
| Strontium | 6.26E-05 | | 7.04E-07 | -3.83E-04 | -3.20E-04 | 6.21E-05 | | 6.99E-07 | -3.80E-04 | -3.17E-04 |
| Sulphate | 2.28E-04 | | 9.69E-07 | -1.23E-05 | 2.16E-04 | 2.26E-04 | | 9.61E-07 | -1.22E-05 | 2.15E-04 |
| Sulphide | 1.37E-03 | | 5.90E-06 | -7.38E-05 | 1.30E-03 | 1.36E-03 | | 5.94E-06 | -7.32E-05 | 1.29E-03 |
| Sulphur | 3.10E-02 | | 3.35E-04 | | 3.14E-02 | 3.08E-02 | | 3.36E-04 | | 3.11E-02 |
| **Organic emissions to industrial soil** | **5.90E-06** | | **2.64E-07** | **-4.18E-04** | **-4.11E-04** | **5.85E-06** | | **2.62E-07** | **-4.15E-04** | **-4.08E-04** |
| Acetic acid | 2.64E-07 | | 8.81E-08 | | 3.52E-07 | 2.62E-07 | | 8.74E-08 | | 3.50E-07 |
| Oil (unspecified) | 5.55E-06 | | 8.81E-08 | -4.18E-04 | -4.12E-04 | 5.50E-06 | | 8.74E-08 | -4.15E-04 | -4.09E-04 |
| Polycyclic aromatic hydrocarbons | 8.81E-08 | | 8.81E-08 | 0.00E+00 | 1.76E-07 | 8.74E-08 | | 8.74E-08 | | 1.75E-07 |

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