Deliverable Report

D8.2: Report on Life Cycle Assessment of O&M activities offshore with a detailed inventory

ROMEO

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Document Contributors

Deliverable responsible		Athanasios Kolios	
Contributors	Organization	Reviewers	Organization
Athanasios Kolios	University of Strathclyde	Cristian Rodenas-Soler	ADWEN
		Leonardo Casado Elena Reig	ZABALA
		Teresa Ojanguren-Fernandez	IBERDROLA

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Abbreviation	Description
CAPEX	Capital Expenditure
ELCA	Environmental Life Cycle Assessment
FinEx	Financing Expenditure
GHG	Greenhouse Gas
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OWT	Offshore Wind Turbine
ROMEO	Reliable O&M decision tools and strategies for high LCoE reduction on Offshore wind
WACC	Weighted Average Cost of Capital

1. Executive Summary

This report documents the background of the development of the Environmental Life Cycle Assessment (ELCA) module of the integrated impact assessment tool, which is delivered as part of WP8 of the ROMEO project. This is the first time that such a functionality is included in an impact assessment tool. This module draws upon the individual components of the framework that has been documented in deliverable D8.1 and through emission unit values adopted from the most up-to-date databases, returns aggregate values of environmental key performance indicators (KPIs) which allow comparison of different operational management strategies.

After a short introduction on the relevance of environmental assessment to the development of renewable energy technologies, a systematic literature review is included, presenting the most recent and extensively cited relevant studies. Next, the structured methodology documented in ISO 14040 is introduced in a practical way, as this is the approach that implementation will follow. Subsequently, the interfaces between the cost/revenue model and the ELCA module are reported, while the report ends with an outlook of future activities.

2. Introduction

Wind energy is nowadays an alternative to conventional energy generation technologies. Although it is considered a ‘clean’ energy technology, as during operation limited emissions are accounted for, considering the life cycle of assets from raw material production all the way to decommissioning, environmental impacts from human activities occur and should be quantified. This can allow for a more thorough assessment of key contributors and qualify opportunities for greenhouse gas (GHG) emissions reductions ensuring that the benefit that is actually achieved is considerable [1].

Life cycle assessment (LCA) is a widely used method to study the environmental burdens of industrial processes and has extensively been applied to evaluate the performance of different renewable and non-renewable sources [2]. Typically, the stages of the life cycle of energy production systems may include all or part of the following [3], [4]:

(i) fuel production
(ii) facility construction,
(iii) facility operation and maintenance, and
(iv) dismantling.

Specifically for offshore wind energy applications, the ‘fuel production’ stage is not directly applicable (although fuel is required for transportation purposes, it is not required for production). As far as the ‘facility construction’ phase is concerned, this accounts for the production of raw materials, including steel for the support structure and tower, composite materials for the blades, coper for the generator etc. It further considers emissions during fabrication, transportation and installation of the units. The ‘facility operation and maintenance’ includes emissions related to the transportation of staff and spare parts through vessels and helicopters. Finally dismantling, or decommissioning as it is most commonly known in offshore wind applications, accounts for the activities related to the end of life of the asset where components are taken apart and are partially recycled, reused or landfilled. The latter stage can illustrate environmental benefits depending on the scenario selected as emissions for subsequent uses can be reduced if recycled materials are used. Properly specifying the boundaries of each stage is crucial so that materials and associated processes are not left out from the analysis. Aim of the assessment is to identify the critical contributing factors in the overall emissions so as to inform selection of relevant operational management strategies.

This report documents the background of the development of the Environmental Life Cycle Assessment (ELCA) module of the integrated impact assessment tool which is delivered as part of WP8 of the ROMEO project. This is the first time that such a functionality is included in an impact assessment tool. This module draws upon the individual components of the framework that has been documented in deliverable D8.1 and through emission unit values adopted from the most up-to-date databases, returns aggregate values of environmental key performance indicators (KPIs) which allows comparison of different scenarios. It should be noted that the assessment will focus primarily on emission-related KPIs rather than other environmental impacts.

Figure 1 illustrates the different stages of the life cycle of an offshore wind farm [5].

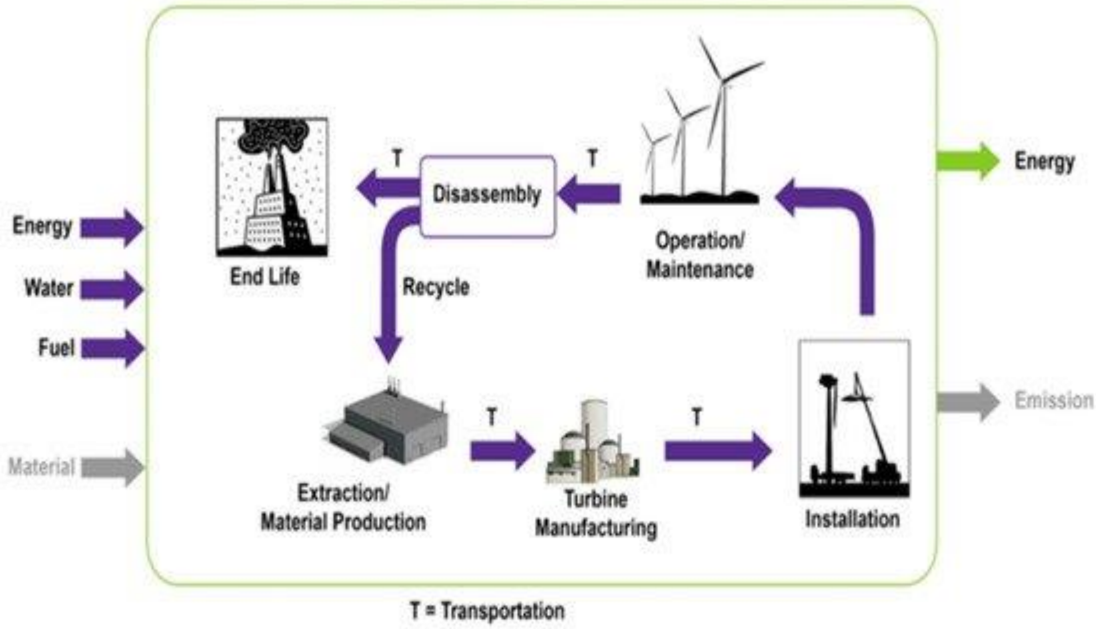

Figure 1: System boundary for the life cycle assessment (LCA) study [6]

3. Literature review

A systematic literature review has taken place using the Scopus database in order to identify relevant information and current trends in the existing literature. The reason that a systematic literature review was selected as a method is that it is based on certain keywords and hence findings of the review can be replicated by other researchers. Scopus is chosen as the database to be used since it accumulates the most credible sources from the international literature. Based on the last 5 years (2014-2019) using the key words ‘offshore’, ‘wind’ and ‘lca’, 37 results returned out of which 29 are directly relevant to the aim of this report. Further 10 papers are considered the most cited since 2000 with more than 30 citations. These references are summarised below.

Wang et al [7] studied the life-cycle green-house gas emissions of onshore and offshore wind turbines using life cycle assessment (LCA) to estimate the life-cycle greenhouse gas (GHG) emissions of onshore and offshore wind turbines with the nominal capacity of 2 MW, to advance understanding of onshore and offshore wind energy and to inform policy, planning, and investment decisions for future growth of wind power. Tomporowski et al [8] performed a comparison analysis of the impact of particular material existence cycle stages of land-based and offshore wind power plant blades on the environment. Tomporowski et al [9] performed an assessment of energy use and elimination of CO2 emissions in the life cycle of an offshore wind power plant farm, developing a mathematical model for efficiency in the design, manufacture, use and management of offshore wind power. Tsai et al [10] performed a Life Cycle Assessment of offshore wind farm siting and the effects of locational factors, lake depth, and distance from shore, conducting a process-based life cycle assessment to compare 20 OWF siting scenarios in Michigan's Great Lakes for their cumulative fossil energy demand, global warming potential, and acidification potential. Bonou et al [11] assessed the environmental impacts related to the provision of 1 kWh to the grid from wind power in Europe and to suggest how life cycle assessment can inform technology development and system planning for four representative power plants onshore (with 2.3 and 3.2 MW turbines) and offshore (4.0 and 6.0 MW turbines) with 2015 state-of-the-art technology data provided by Siemens Wind. Lloberas-Valls et al [12] performed a detailed "cradle-to-gate" life-cycle assessment of the 15-MW 2GHTSDDSG and PMDDSG, using GaBi 6 commercial software and PE International Professional and Ecoinvent 2.2 databases, as a result of quantifying each component required for the production. Angelakoglou et al [13] discussed a number of issues regarding wind turbines positioning in terms of land, coastal and offshore installation, evaluating technical, environmental, energy, social and economical parameters, and providing thus a holistic assessment of the systems under examination. Reimers et al [14] assessed specific GHG (greenhouse gas) emissions as a function of the site conditions, the wind turbine technology and the O&M necessities. Hoyme et al [15] studied the Nonwoven geotextile scour protection at offshore wind parks, application and life cycle assessment.

Bessau et al [16] presented a tailored comprehensive impact assessment methodology for fleets of renewable energy systems based on Life Cycle Analysis and its application to Danish wind turbines fleet through an online platform LCA_WIND_DK. García-Gusano et al [17] performed a prospective analysis of the energy security of a national energy system, through a novel methodological framework combining Life Cycle Assessment and Energy Systems Modelling. Elginoz and Bas [18] presented a Life Cycle Assessment of a multi-use offshore platform, combining wind and wave energy production on a novel semi-submersible floating platform. Soerensen et al [19] assessed the environmental and economic performance of a combined wind-wave energy converter over its entire lifecycle, covering embedded costs, energy balance and carbon footprint, right from the raw materials to the final decommissioning. Myhr et al [20] presented a comprehensive analysis and comparison of the levelised cost of energy (LCOE) for the following offshore floating wind turbine concepts: Spar-Buoy (Hywind II), Tension-Leg-Spar (SWAY), Semi-Submersible (WindFloat), Tension-Leg-Wind-Turbine (TLWT) and Tension-Leg-Buoy (TLB) and for a generic commercial wind farm consisting of 100 five megawatt turbines. Amponsah et al [21] presented a review of renewable energy technologies (RETs) for electricity and heat generation and estimated life cycle GHG emissions from a range of renewable electricity and heat generation technologies. Arvesen et al [22] contributed to an improved understanding of the environmental implications of offshore power grid and wind power development pathways through investigating the impacts of a North Sea power grid enabling enhanced trade and integration of offshore wind power and assessing the benefit of the North Sea grid and wind power through a comparison of scenarios for power generation in affected.

Middel and Verones [23] studied marine noise pollution impacts and the case of cetaceans in the North Sea within life cycle impact assessment, presenting a first approach for the integration of noise impacts on marine ecosystems into the LCA framework by developing characterization factors (CF) for the North Sea. Huang et al [24] presented a life cycle assessment and net energy analysis of offshore wind power systems, attempting to evaluate the environmental impact and energy benefit of offshore wind power systems using life cycle assessment (LCA) and net energy analysis. Kadiyala et al [25] performed a characterization of the life cycle greenhouse gas emissions from wind electricity generation systems, evaluating the life cycle greenhouse gas (GHG) emissions from different wind electricity generation systems by (a) performing a comprehensive review of the wind electricity generation system life cycle assessment (LCA) studies and (b) statistically evaluating the life cycle GHG emissions (expressed in grams of carbon dioxide equivalent per kilowatt hour, gCO2e/kWh). Gumus et al [26] proposed a generic 9-step fuzzy MCDM method to solve sustainable energy decision-making problems using a combination of three different techniques: (1) an intuitionistic fuzzy entropy method to identify the individual importance of phases and criteria; (2) an IFWGA operator to establish a sub-decision matrix with the weights applied to all relevant attributes; and (3) an IFWAA operator to build a super-decision matrix with the weights applied to all of the life-cycle phases considered. Raadal et al [27] presented specific life cycle GHG emissions from wind power generation from six different 5MW offshore wind turbine conceptual designs, calculating the energy performance, expressed by the energy indicators Energy Payback Ratio (EPR) Energy Payback Time (EPT).

Yang et al [28] performed a life-cycle energy and environmental emissions assessment of a typical offshore wind farm in China through a process-based life cycle inventory (LCI) model to calculate the life-cycle energy and emissions of offshore wind power in China based on the country's first offshore wind energy project. Yang et al [29] performed an analysis of energy consumption and greenhouse gas emission of an offshore wind farm in China through a hybrid life cycle assessment model to facilitate the accounting of the energy consumption and GHG emission of Donghai bridge offshore wind farm in Shanghai. Chipindula et al [30] studied the life cycle environmental impact of onshore and offshore wind farms in Texas focusing on the sensitivity analysis for material and manufacturing stages, attempting to quantify and mitigate the potential environmental impacts of individual stages (material extraction/processing, turbine manufacturing, installation, operation & maintenance and disassembly) toward life cycle impacts of wind farms at three locations (onshore, shallow-water and deep-water) in Texas and the gulf coast. Mroziński and Piasecka [31] presented prospects for development of global, European and domestic markets of offshore wind power industry and a comparative analysis of environmental impact of an offshore and land-based 2MW wind power electric plant by using LCA method and Ecoindex - 99 (Ekowskaznik 99) modelling. Noori et al [32] aimed to quantify the direct and supply chain related indirect environmental impacts of onshore and offshore wind energy technologies in the United States through a hybrid life cycle assessment (LCA) model. Noori et al [33] aimed to quantify the socio-economic and environmental impacts of producing electricity by wind power plants for the US electricity mix, quantifying all direct and supply chain-related impacts of different onshore and offshore wind turbines through a hybrid economic input-output-based triple bottom line (TBL) life cycle assessment model.

Jensen [34] evaluated the environmental impacts of recycling wind turbines analysing the decommissioning and recycling process, with special considerations given to the environmental aspects of a theoretical 100% recyclability scenario.

In addition, the most highly cited papers are included below.

Schleisner [35] concentrated on the assessment of energy and emissions related to the production and manufacture of materials for an offshore wind farm as well as a wind farm on land based on a life cycle analysis (LCA) model. Weinzettel et al [36] evaluated additional environmental burdens to investigate whether they can be rebalanced or even offset by better wind conditions, presenting a prospective life cycle assessment (LCA) study of one floating. Dolan and Heath [37] performed a systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems to determine the causes of and, where possible, reduce variability in estimates of life cycle greenhouse gas (GHG) emissions, screening approximately 240 LCAs of onshore and offshore systems which yielded 72 references meeting minimum thresholds for quality, transparency, and relevance. Arvesen and Hertwich [38] critically reviewed present knowledge of the life cycle environmental impacts of wind power, finding that the current body of life cycle assessments (LCA) of wind power provides a fairly good overall understanding of fossil energy use and associated pollution. Wagner et al [39] presented a life cycle assessment of the offshore wind farm alpha ventus, comparing findings to that of Germany's electricity mix and concluding that alpha ventus had better indicators in nearly every investigated impact category. Finally, Arvesen and Hertwich [40] investigated the potential environmental impacts of a large-scale adoption of wind power to meet up to 22% of the world's growing electricity demand, building on life cycle assessments of generic onshore and offshore wind farms, meant to represent average conditions for global deployment of wind power.

Based on the above review of literature it can be observed that although many of the studies share the same aim, there is a degree of inconsistency in the results produced. This is due to the different boundaries specified as well as the databases chosen which can in fact significantly influence the results. In any case, these reported results can be valuable for validation/verification purposes for the module that will be developed. Finally, although some studies combine energy generation with life cycle assessment studies, none has been found to integrate the environmental study to a full cost model and with an integrated O&M analysis tool. To this end, the aim of WP8 and specifically subtasks related to the integration of the LCA module is valid and will contribute to the existing body of knowledge, as it will allow for a number of scenarios to be simulated in order to quantify the cost of CO2 mitigation strategies.

4. ISO 14040

Life Cycle Thinking – ‘from cradle to grave’

Life Cycle Assessment (LCA) is a comprehensive technique for assessing the environmental aspects and impacts associated with a product or a service over its service life. Despite the fact that such a tool may give credits to environmental claims over a product for marketing purposes, its real contribution is the life cycle thinking that introduces. In order to obtain a deep understanding about the environmental performance of a product, a systemic approach should be adopted. This idea is referred to as a “cradle to grave” approach.

Environmental Life Cycle Assessment is a tool for [41]:

- Identification of opportunities for design improvements by analyzing the contribution of the life cycle stages to the overall environmental load;
- Decision making by industry regarding production processes and planning among different feasible options;
- Support in policy development;
- Selection of environmental performance criteria;
- Benchmarking and environmental declarations;
- Marketing purposes.

Step by step approach to Environmental LCA/ ISO 14040/ISO 14044

The first applications of a life cycle analysis initiated back to 1970’s. Currently, ELCA is framed by two ISO Standards. The ISO 14040:2006 [42] describes the principles and the framework and the ISO 14044:2006 [41] provides the requirements and the guidelines for conducting an ELCA.

According to these international standards, a LCA study comprises of the following four phases (Figure 2):

- Goal and scope definition
- Inventory analysis (LCI)
- Impact Assessment (LCIA)
- Interpretation

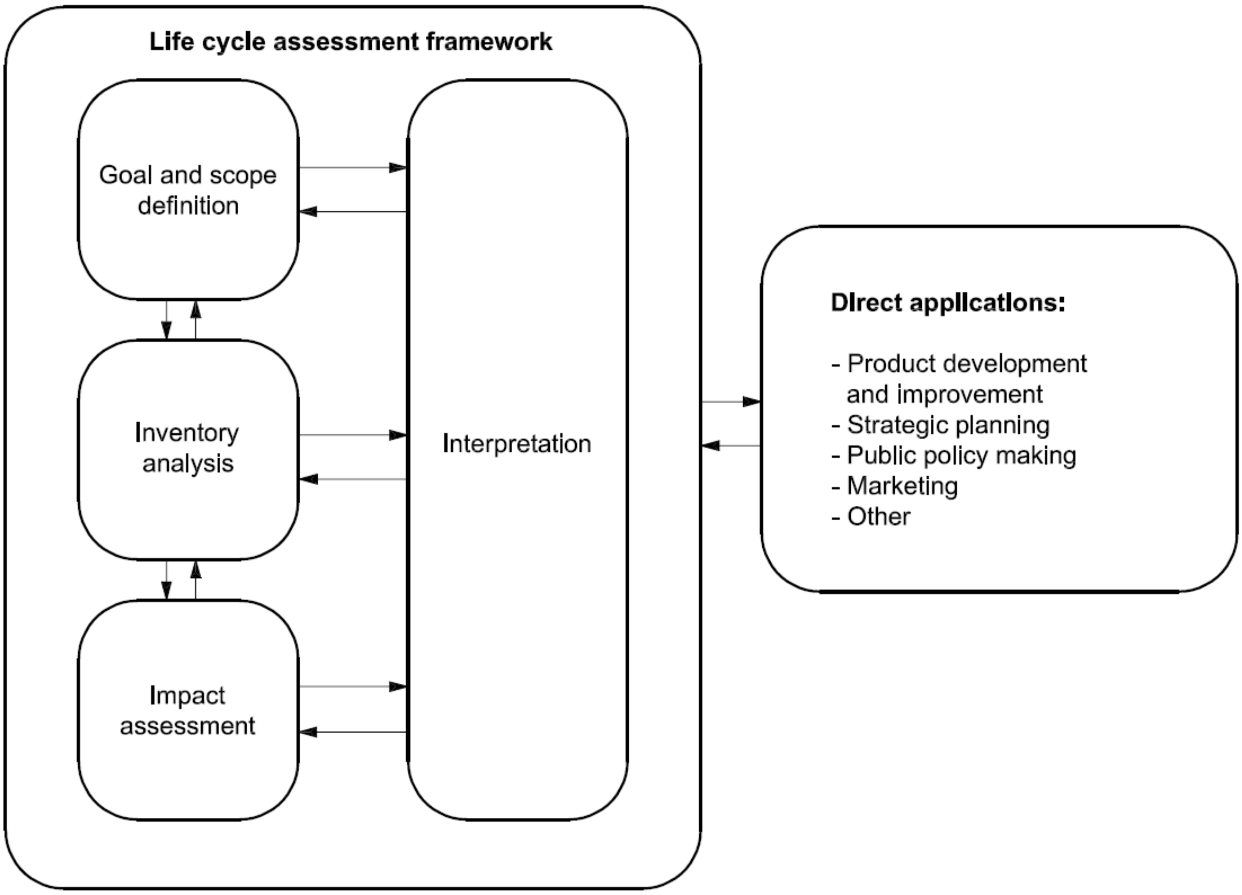

Figure 2: LCA stages [42]

During the first phase (Goal and scope definition) the practitioner should describe the application and the reasons for the study. Furthermore, in order to develop a realistic model it is essential to provide the following information:

- Product systems – performance characteristics and functional unit or reference flows (allocation issues)
- System boundaries - sub-products
- Cut - off criteria – determine level of detail
- The impact assessment methodology which will be followed
- Data requirements (time boundaries, geographical and technological criteria)

In the second phase (Inventory analysis) the practitioner collects all the necessary data which can be classified as follows (Figure 3):

- Physical data (energy requirements and resources ie materials)
- Environmental releases (air, soil, water)
- Waste or co-products

- Other environmental aspects

The procedure for the Inventory Analysis is presented in Figure 3 [41]:

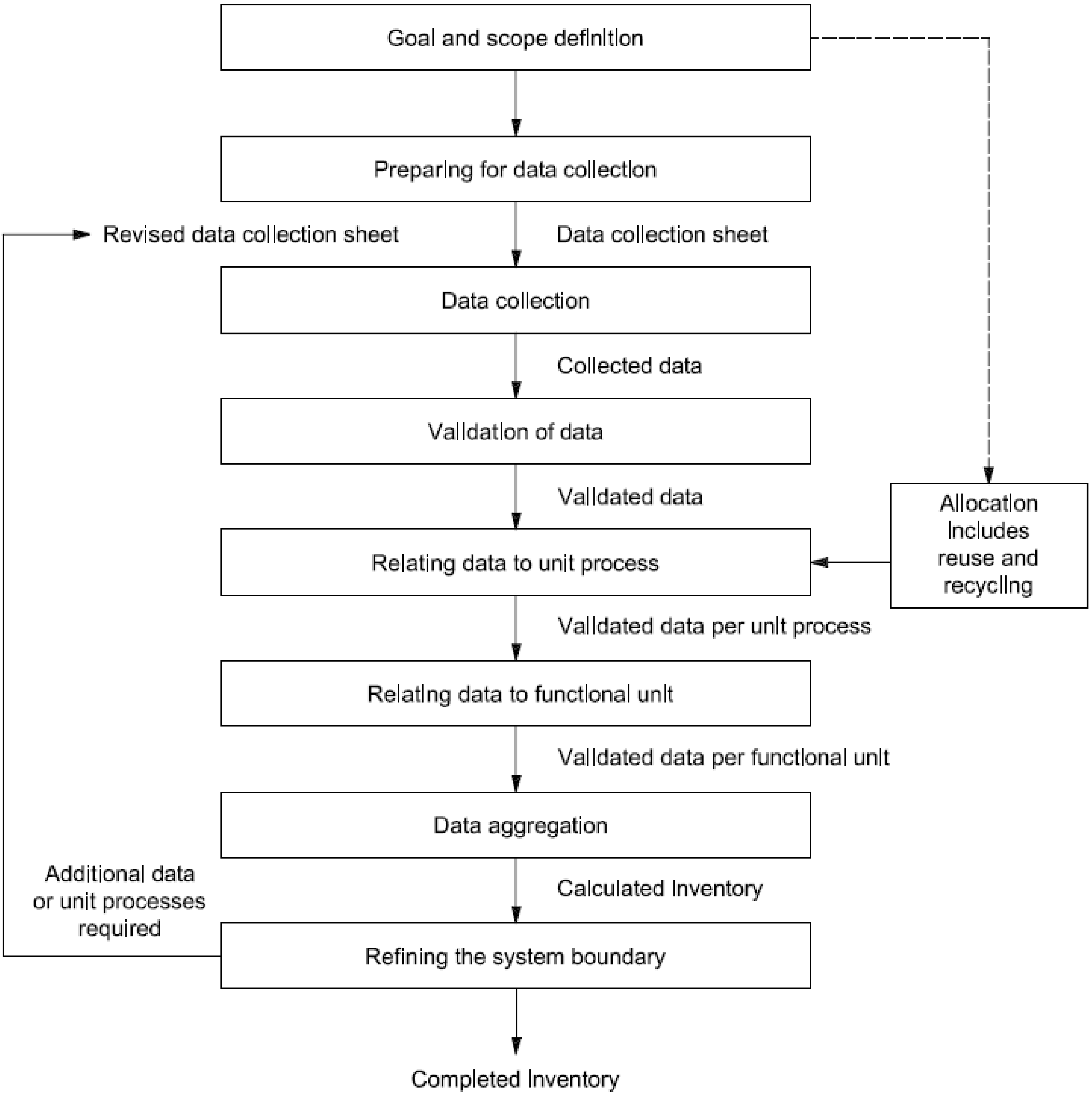

Figure 3: Simplified procedures for inventory analysis [41]

In the Impact Assessment phase the potential contribution of all the aggregated results from the Inventory Analysis is evaluated and calculated. The process of assigning all the inventory data to environmental impact categories/results by following the environmental mechanism is illustrated in Figure 5. ISO 14044:2006 [41] highlights that the accuracy of this step depends highly on the quality of the inventory data.

Classification is the step where the LCI results are assigned into impact categories.

Characterization is the second step, where the LCI results by following a characterization model (equivalency factors which are scientifically and technologically validated) are converted into a measurable indicator (Figure 4).

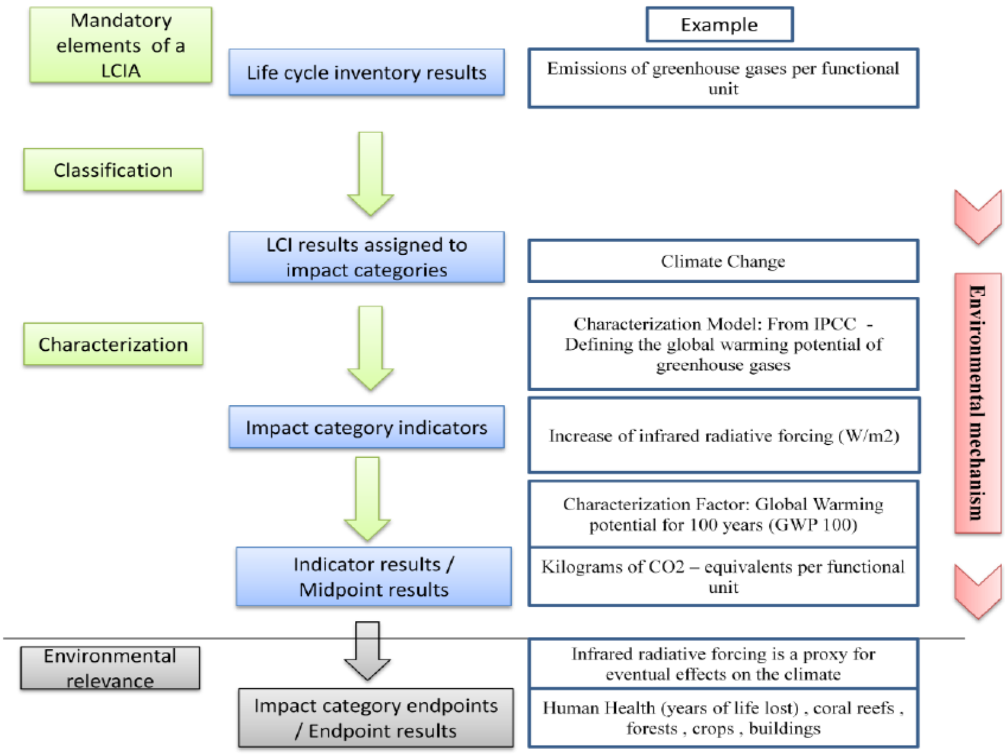

Figure 4: Life Cycle Impact Categories

In the Impact Assessment phase, the optional elements which can be highly subjective are the following:

- Normalization: Calculates the magnitude of each impact category;
- Grouping: The impact categories are allocated according to their environmental relevance to endpoint results (damage assessment);
- Weighting: Evaluates the importance of impact categories and gives a value to their damage result;

The final phase of an Environmental LCA (Interpretation), according to ISO Standards should include the following:

- Identification of significant issues related to the life cycle of the product;
- Evaluation of the results;
- Reporting in a transparent way;

- Conclusions and recommendations on a factual basis.

During the Interpretation phase all the data are evaluated for their completeness, accuracy and consistency with the initial goal and the scope of the study. Additionally, a sensitivity analysis can be performed for the evaluation of critical parameters/inputs of the model developed during the LCA study.

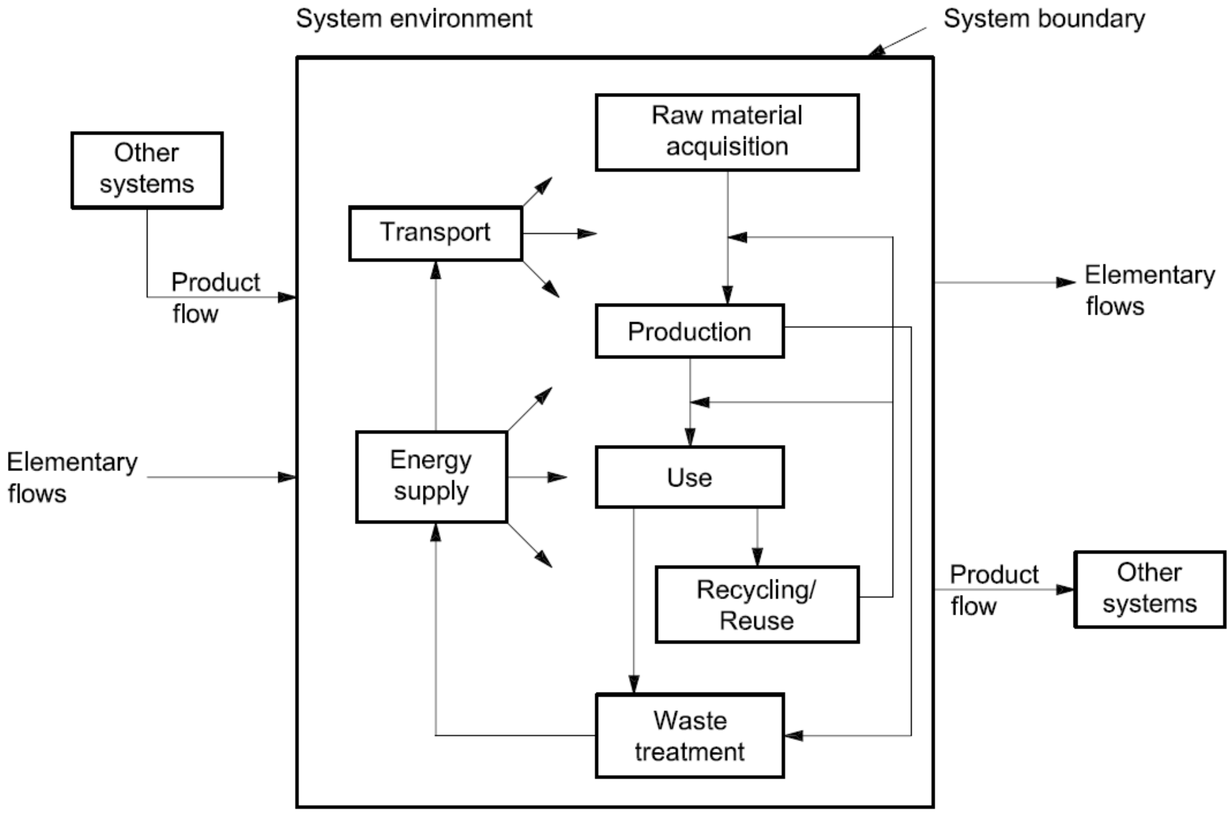

Figure 5: Example of a product system for LCA [42]

Use of databases in LCA

To be able to perform life cycle assessments (or any other type of environmental assessment) of a specific good or service, one needs to have inventory data for the complete supply chain. Due to the amount of data needed in order to be able to perform a LCA study of a full supply chain it is practically impossible to collect and organize data of the complete background system without having access to a background LCI database. For this reason, the ecoinvent database will be used in this project as it is the most complete available and widely adopted by industry for several applications [43].

The ecoinvent database is a background database which allows the user to focus on collecting data for a specific foreground system, while using ecoinvent for the background. The ecoinvent database is currently the most widely used LCI database which offers fully interlinked unit process supply chains for all products present in the database. Datasets cover all relevant environmental flows, such as resource extractions, land use and emissions, as well as all material and energy inputs and products of an activity. By offering data on the unit process level, the ecoinvent database ensures transparency over the whole supply chain. The ecoinvent database version 3 increases transparency by allowing data providers to use mathematical relations. Thus, the users can see not just the amount of certain exchange, but also the underlying function of how it was calculated. [44]

Environmental considerations on Wind Turbines - application of 'ELCA thinking'

As every product, wind turbines and wind farms have an environmental impact which has been the subject of several LCA studies regarding the evaluation of the environmental performance of wind power generation systems as seen through the literature review in previous section. Several projects in a European basis have been completed having as an objective to provide a better view on the environmental impacts and other externalities related to wind power energy systems.

Despite the fact that there is a plethora of LCA studies for wind turbines and wind farms, the basic concept of life cycle thinking which provides the methodological base for all these studies is the same.

- The manufacturing stage usually comprises of all raw materials, energy and transportation (material from source to manufacturing or assembly unit) required for the main and secondary components of the structure and the infrastructure in the case of a wind farm.
- The installation stage takes into account the transportation and the energy consumption required for the onsite installation. Distances between assembly and erection point are site depended for both onshore and offshore applications.
- The operation and maintenance stage includes all the routine inspections and preventive/corrective maintenance required (energy, materials, transportation) for ensuring the efficient operation of the equipment. Replacements in some components may be included.
- Finally the end of life stage includes the decommissioning and the final disposal of the wind turbines. Recycling is a beneficial practice regarding the total environmental impact of the life cycle of a wind turbine or farm.

In the next section an application specific discussion of the individual phases will be presented.

Software for LCA

Although for this project a special module for LCA will be developed, it seems appropriate to present a comparative table of commercially available tools (Table 1).

Table 1: Software tools for LCA calculation [45]

Tool	Developer	Approach	Web
AIST-LCA 4	National Institute of Advanced Industrial Science and Technology (AIST), Japan	Generic	www.aist-riss.jp/main/
Athena	Athena Sustainable Materials Institute, Canada	Building and construction	www.athenasmi.org/
BEES 4.0	National Institute of Standards and Technology, USA	Building materials	www.nist.gov/el/economics/BEESSoftware.cfm
CMLCA 4.2	Leiden University, Institute of Environmental Sciences (CML), Holland	Generic	www.cml.leiden.edu/software/
E^3DATABASE	Ludwig-Bölkow-Systemtechnik GmbH, Germany	Generic	www.e3database.com/
EARTHSTER 2 TURBO	GreenDelta GmbH	Generic	www.greendelta.com/
ECO-BAT 4.0	Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud, Switzerland	Building and construction	www.eco-bat.ch/
GaBi	Pe-International	Generic	www.gabi-software.com/
GEMIS	Oeko Institut, Germany	Generic	www.gemis.de
LEGEP	LEGEP Software GmbH, Germany	Generic and Building	www.legep.de/?lang=en
OpenLCA	GreenDelta GmbH	Generic	www.openlca.org/
REGIS	Sinum AG-EcoPerformance Systems	Generic	www.sinum.com/
SABENTO	ifu Hamburg GmbH, Germany	Chemical	www.sabento.com
SIMAPRO	PRé-Consultants	Generic	www.pre-sustainability.com/
SULCA 4.2	VTT Technical Research Centre of Finland	Generic and forest	www.vtt.fi/index.jsp
TEAM	Ecobilan Pricewaterhouse Coopers	Generic	www.ecobilan.pwc.fr/en/boite-a-outils/team.jhtml
TESPI	ENEA, Italy	Generic	www.elca.enea.it/
UMBERTO	ifu Hamburg GMBH	Generic	www.umberto.de/en/
USES-LCA 2.0	Netherlands Center For Environmental Modeling	Terrestrial, freshwater, and marine ecosystems	www.cem-nl.eu/useslca.html

5. Development of LCA module for impact assessment tool

Brief presentation of the cost revenue model

The integrated Life/cycle cost/revenue model consists of the following, as illustrated in Figure 6 [46]:

(i) CAPEX module, consisting of the D&C, P&A, I&C and D&D phases of the OW farm;
(ii) General site characteristics module detailing the weather conditions, water depth, distance from port, vessels, cost of personnel etc.;
(iii) FinEx module with parameters on financing expenditures, such as weighted average cost of capital (WACC), inflation rate, equity and debt ratio, etc.,
(iv) OPEX module incorporating data from the O&M module presented earlier;
(v) Revenue module, which considers the net power generation, the energy policy scheme in place for supporting the technology, namely the Contracts for difference (CfD) scheme, and the market electricity price to derive the revenues relevant to the investment.

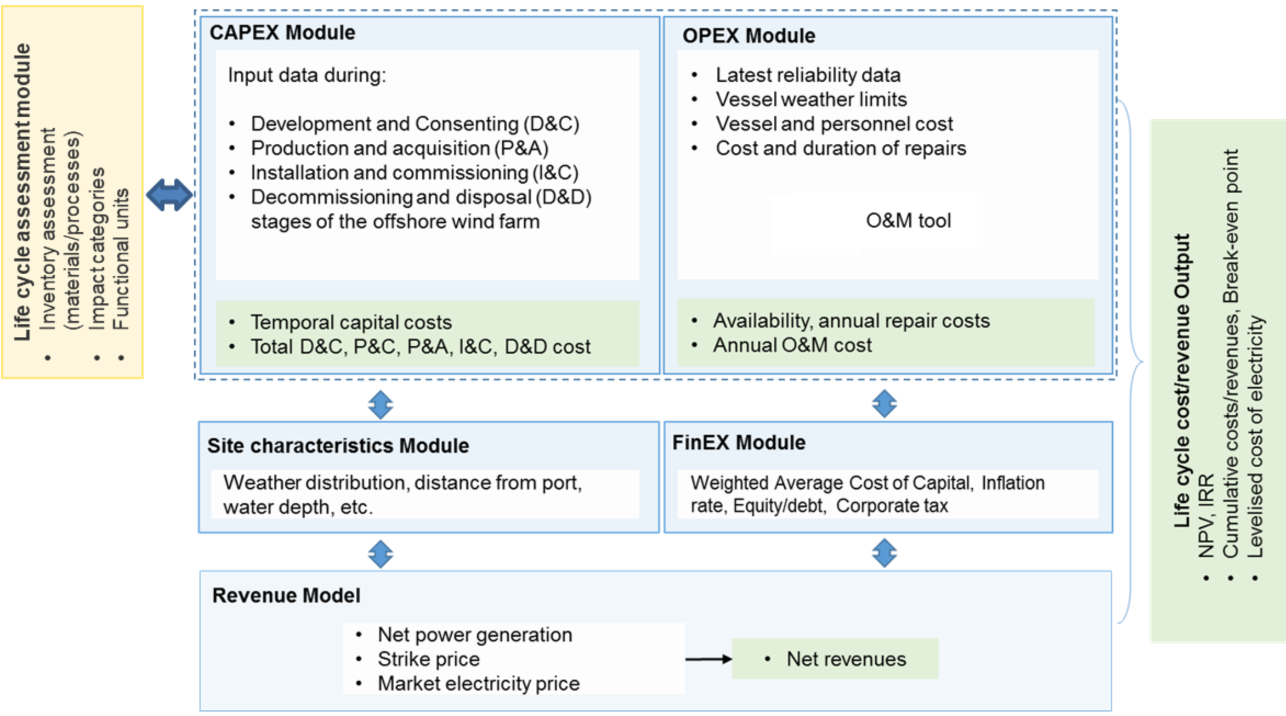

Figure 6: Methodological framework

Extraction of information from cost and O&M model to LCA module

Figure 7 and Figure 8 below present the boundaries of a wind turbine system from an LCA perspective. In this section the individual phases presented earlier will provide input to the dedicated LCA module that will be developed as part of the ROMEO project.

Rotor	Nacelle	Tower	Foundation	Others
• Cast Iron • Epoxy Resin • Steel • Prepreg	• Cast Iron • Steel • Copper • Chromium • Aluminium • Electronics • Oil	• Steel	• Concrete • Steel	• Polyethylene • Coated zinc

Figure 7: Wind turbine materials of major assemblies

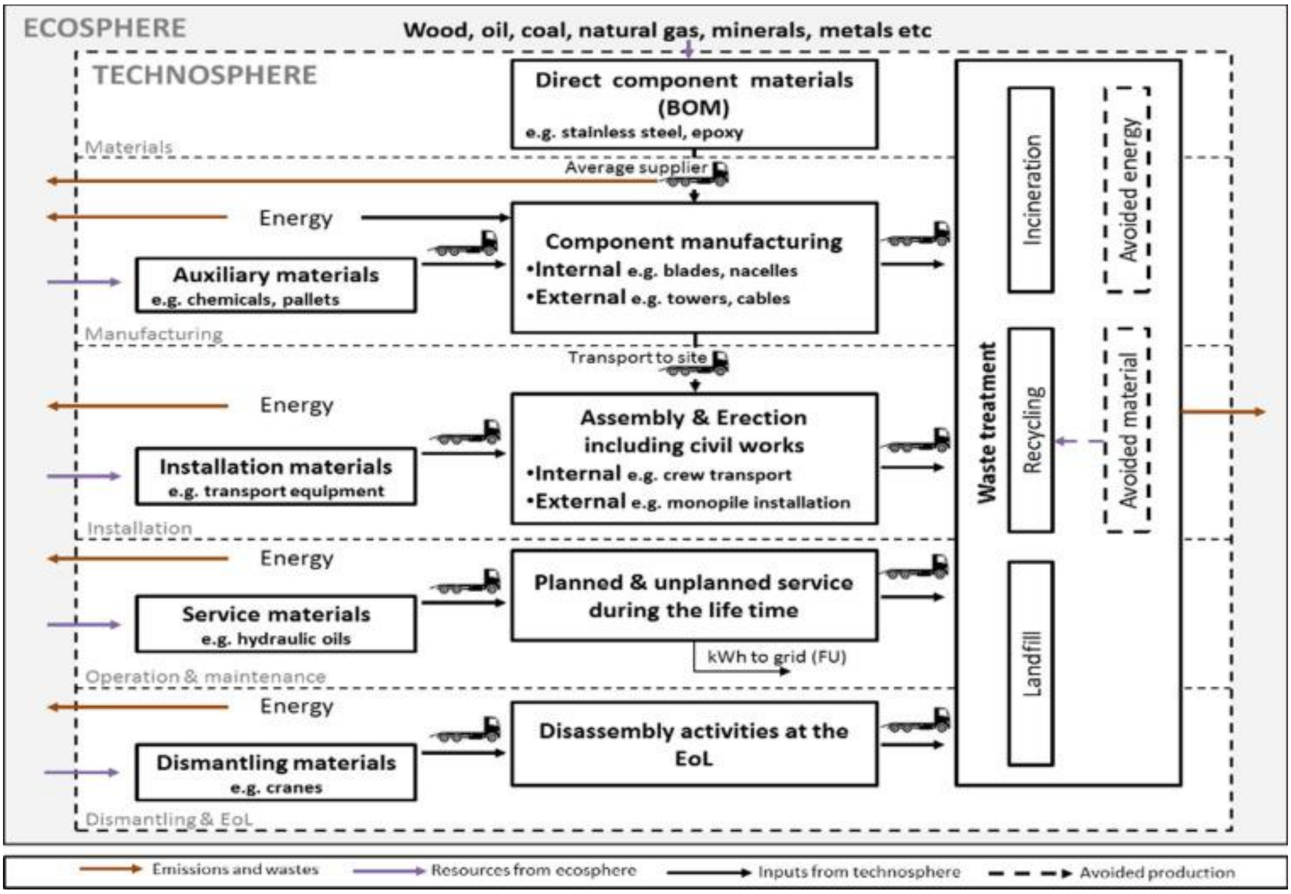

Figure 8: System boundaries covering all life cycle stages of all wind power plants [47]

CAPEX module

The production and acquisition module, will produce, based on the most up-to-date parametric equations that have been included, the mass of different components and associated processes. Related processes in this stage include cutting, welding, forging, composites forming, electronics manufacturing etc. Further, transportation to the fabrication yard, from there to the deployment port, using appropriate means of transportation will be accounted for, considering the unit of the tn.km. As these quantities depend on the actual locations of the fabrication plants, further inputs will be required from the user. This will be incorporated to the site's characteristic module.

The phase of installation and commissioning, consider further processes including transportation to the deployment location using barges, lifting using high capacity vessels and piling using hydraulic hammers as well as transportation of relevant crew.

Finally, decommissioning and disposal should take into account processes like lifting, cutting and transportation of subassemblies and personnel to the port.

OPEX module

Here, a series of outputs from the O&M simulations are accounted for, including all spare parts that will be required (which will be translated into materials), number of trips per vessel required, as well as downtime in order to consider the total electricity produced for calculation of the emissions and other environmental KPIs.

Figure 9, summarises the processes relevant to the life cycle of the asset, including transportation and processing of materials. This will be used in order to model the ELCA module of the impact assessment tool. Figure 10, presents the inventory analysis of a typical offshore wind turbine (OWT) generator. In the appendix of this report, a table of relevant references from literature is included, providing useful data for the implementation of the module.

Functional unit and output variables

Functional unit quantifies performance of a product system for use as a reference unit. This is specifically important for comparison of different technologies or different scenarios from an environmental perspective.

For the purpose of this study, focus will be on the CO_2 emissions and the selected functional unit will be kg-CO2/kWh produced. Further environmental KPIs will also be considered, potentially including particular impact indicators such as climate change, primary energy consumption ,water depletion, abiotic resource depletion, depletion of the ozone layer, human toxicity, photochemical ozone formation, particulate matter, acidification, ecotoxicity, and land use, among others.

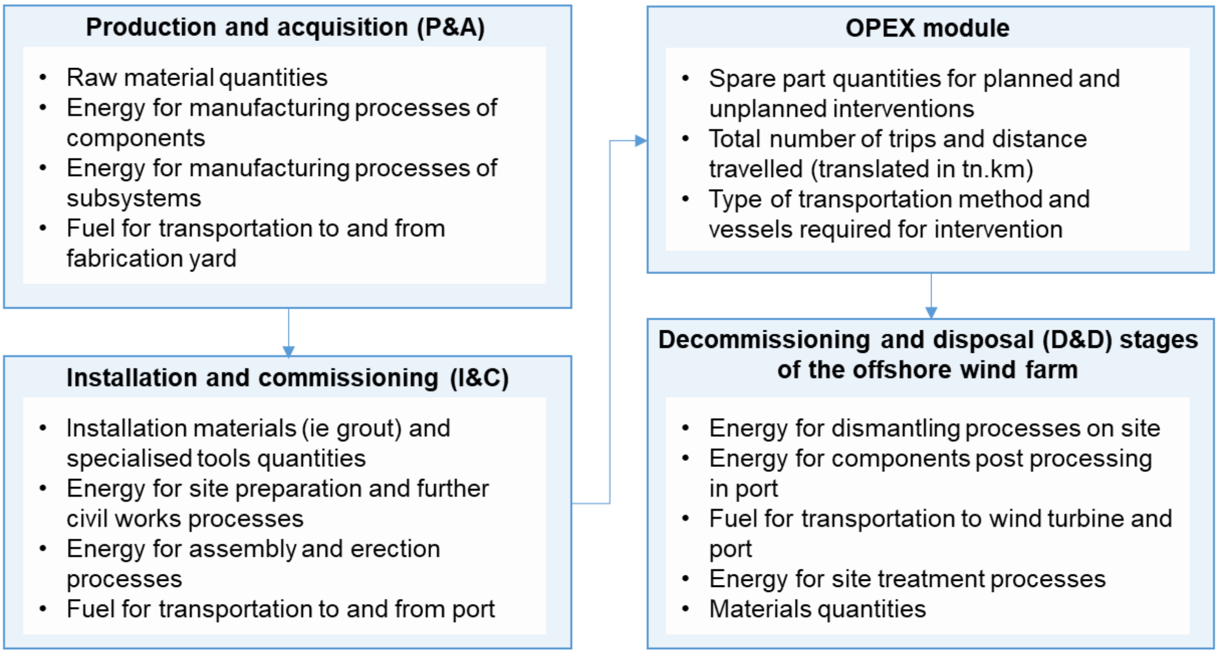

Figure 9: Life cycle process and materials flow of offshore wind turbines

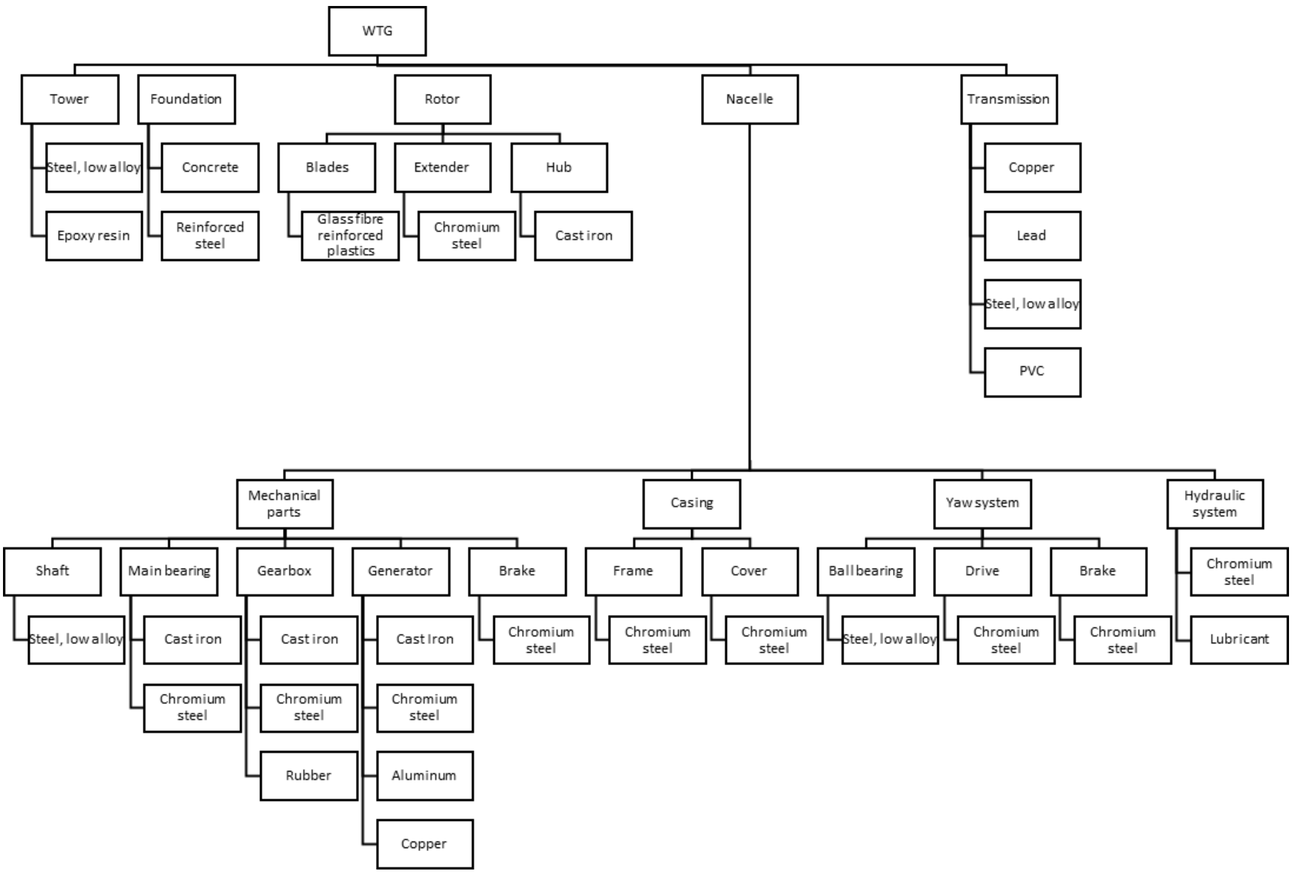

Figure 10: WTG inventory analysis

6. Conclusions and outlook on future work

This report documents the background of the development of the Environmental Life Cycle Assessment (ELCA) module of the integrated impact assessment tool, which will be delivered as part of WP8 of the ROMEO project. After a short introduction on the relevance of environmental assessment to the development of renewable energy technologies, a systematic literature review was performed, presenting the most recent and highly cited relevant studies. Next, the structured methodology documented in ISO 44010 is presented in a practical way, as this is the approach that implementation will follow. Subsequently, the interfaces between the cost/revenue model and the ELCA module are reported, while the report ends with this outlook of the future work.

Based on the review of literature that was performed it was confirmed that although many of the studies reported so far share the same aim, there is a degree of inconsistency in the results produced, hence the aim of WP8 and specifically subtasks related to the integration of the LCA module is valid and will contribute to the existing body of knowledge.

Moving forward, the ELCA module will be implemented based on the method presented in sections 4 and 5 and relevant inventory analysis, while unit emissions will be adopted by the ecoinvent database which was identified to be the most suitable for the purpose of this work. The integrated tool that will be developed, will allow for a sensitivity analysis to take place identifying key contributors to life cycle emissions related KPIs and run a number of scenarios to not only qualify emission reduction strategies but also to quantify the additional/reduced emissions that variations to CAPEX and OPEX due to the different maintenance strategies that will qualify as part of the ROMEO project.

7. Appendix

Content	Reference
Assumptions for material breakdown used in modelling components of Enercon E-66 wind turbine and TIOs 1–4	[48]
Material inventory of the DBOWF (quantities of materials for 3.6 and 5 MW wind turbines)	[49]
Inputs for 2MW offshore wind turbine (functional breakdown system, materials and quantities)	[50]
Aggregated inventory dataset for offshore substation	[51]
Quantities of materials used for the wind power system (including transmition)	[52]
Numbers of vessels and workdays and the usage of fuels in the installation stage	[52]
Modelling assumptions for the EoL treatment of the main materials in wind power plant systems	[47]
Corresponding Masses and Detailed Materials of the Wind Turbines for different life cycle phases (manufacturing, construction and erection, operation and maintenance, transportation)	[53]
Materials and masses for the adjusted NREL 5 MW offshore turbine and corresponding Ecoinvent processes used in the analyses.	[54]

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