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Life Cycle Assessment for marine renewables

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Life Cycle Assessment for marine renewables

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Summary

This reports reviews and offers advice on obtaining realistic and comparable results for Life Cycle Assessment (LCA) for marine energy technologies. It starts with a brief introduction to LCA and the ISO standards that regulate this process and then focuses on the different phases of the analysis. Wherever possible, in each of these phases, it shows data and examples from LCAs performed on marine energy technologies or other renewable technologies (especially wind).

CONTENTS

1 INTRODUCTION TO LIFE CYCLE ASSESSMENT

Global warming due to emissions of greenhouse gases (GHG) from human activity is probably the single most challenging environmental issue at present. Fortunately science and technology development today can facilitate a transition to a low carbon economy. To select the best pathway requires evaluation of the environmental performance of products and processes in order to minimize GHG emissions, hazardous wastes and other emissions that may provoke significant impacts on the environment.

Energy use is the main contributor to man-made GHG emissions due to combustion of fossil fuels in transport, heating and electricity production. Recent introduction of renewable energy represents one of the partial solutions to solve the carbon dependency in electricity production and minimize our effect on the climate. However, in their construction, use and disposal phases of these technologies, energy is needed and, because the actual energy mixes are based on fossil fuels, CO_2 emissions occur.

Life Cycle Analysis or Assessment (LCA) is a methodical analysis which follows an international standard but requires time and experience, especially in the definition of the different assumptions. The term 'life cycle' indicates that analysis covers all stages in a product's life: it begins with extraction of raw materials from the earth and ends with their ultimate disposal when all materials are returned to the earth, including materials manufacture, production, use, reuse, maintenance, and waste management [1]. Thus it permits assessment of the environmental impacts of each life stage like the CO_2 emissions in the manufacturing of a wind turbine or a wave energy converter. Previous results from the few LCA studies that have been performed to date on wave and tidal devices show good environmental performance relative to conventional power plants or renewables such as solar PV or biomass. The technologies that have the lowest life cycle GHG emissions to date are nuclear, large hydro and wind, followed by wave and tidal energy ([2] and [3]). The early stage of development of marine energy technologies means that LCA analysis has been limited as it can be a time consuming process. However, LCA is useful for product development as it assess all material flows and processes, which permits optimization over the whole life cycle. This important fact has pushed large wind energy companies like Vestas to perform analysis for their wind turbines [4], [5]. In fact, this methodology can be very useful in reducing costs at the same time as minimizing the environmental impacts and an increasing number of companies use LCA to evaluate their products and processes.

This reports aims to review and give advice on the application of LCA in delivering realistic and comparable assessments of marine energy technologies. It starts with a brief introduction to LCA and the ISO standards that regulate this process and then focuses in the different phases of the analysis. Wherever possible it uses examples from LCAs performed on marine energy technologies or other renewable technologies, especially wind.

1.1 ISO STANDARDS

LCA represents a tool to estimate the cumulative environmental impacts resulting from the whole product life cycle, often including impacts ignored in traditional analyses (e.g. raw material extraction, transportation, maintenance process, final disposal, etc). An LCA allows a decision maker to study an entire product system, avoiding the sub-optimization that could result when the focus of the study is on only a single process. The LCA helps to avoid shifting environmental problems from one place to another. Burden shifting can occur from one life-cycle phase to another, from one location to another or from one environmental problem to a different one. By including the impacts throughout the whole product life cycle, LCA enables a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. It is important to note that LCA is always performed relative to a 'functional unit'.

The LCA process is regulated by the International Standards Organization (ISO) 14000 series:

- ISO 14040: 2006 (Environmental management - Life cycle assessment - Principles and framework) [6]
- ISO 14044: 2006 (Environmental management - Life cycle assessment - Requirements and guidelines) [7]

According to the definition given by the ISO standards, LCA is "a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases
- Evaluating the potential environmental impacts associated with identified inputs and releases
- Interpreting the results to help decision-makers to make a more informed decision" [6]

LCA is a procedure constituted by four different phases (Figure 1) [6]:

1. Goal Definition and Scoping - Define the purpose of the study. It includes a description of the studied product, process or activity. Establish the context in which the assessment may be made, identify the functional unit to be used and establish the system boundaries and limitations. This phase includes a description of the method used for assessing potential environmental impacts and which impact categories will be included in the study.
2. Inventory Analysis – Consists of data collection and analysis. For each process within the studied system boundaries, data including energy, water and materials usage and environmental releases (air emissions, water emissions, solid waste disposal, etc.) are quantified. Other types of exchanges or interventions such as radiation or land use can also be included. Data are then processed to produce an inventory of inputs and outputs per functional unit.

3. Impact Assessment – Assess the potential environmental effects of the inventory items identified in the inventory analysis. Contribution to impact categories such as global warming and acidification are evaluated by calculating impact potentials from the LCI results. Economic and social impacts are typically outside the scope of LCA.
4. Interpretation – Evaluate the results of the LCA study to draft conclusions and make decision, taking into account not only the numerical results, but also the boundaries of the system, the quality of data and the sensitivity of results. The interpretation phase can be used to adjust the goal definition or improve the inventory analysis or the impact assessment investigation, showing as the LCA is an iterative process in which all the phases are interdependent, as illustrated in Figure 1. Interpretation may include normalization to provide a basis for comparing different types of environmental impact categories. Although non-compliant with the ISO standards, an impact weighting process is sometimes undertaken to create a single impact measure based on the users' subjective judgment of the relative importance of particular factors.

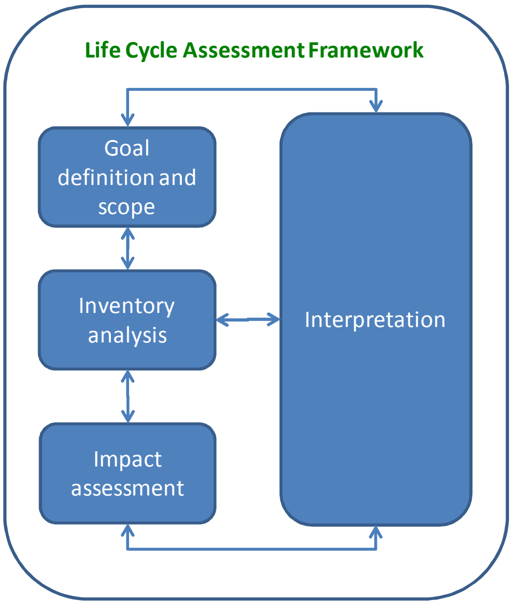


Figure 1 Phases of a LCA (adapted from [6]).

2 LCA FOR MARINE ENERGY TECHNOLOGIES

Examples of LCA for different renewable energy technologies can be found in [5], [8] and [9]. LCAs for marine energy devices have also been published for the Seagen tidal current turbine [2], the Pelamis [3] and Wave Dragon [10] wave energy converters. Several other preliminary analyses for devices like Oyster and Tidal Sails exist but are not yet public domain. In this section, the LCA studies performed on marine energy technologies are reviewed. The aim of this report is to present the methodology and discuss the importance of the assumptions made when performing an LCA with examples of case studies. Baumann and Tillman's [11] introductory book on LCA is recommended as a starting point for LCA. This report follows the structure of [11] as well as the extensive LCA analysis performed by Vestas for their onshore and offshore V80 and V90 wind turbines [4], [5].

2.1 GOAL AND SCOPE

2.1.1 Goal definition

The goals of the LCA for the Vestas V80 wind turbine [4] are: 1) to use life cycle assessments to environmental improvement strategies in connection with product development; and 2) to use LCA-data for preparation of an environmental declaration of contents for electricity produced on turbines. Vestas' updated report [5] on the V90 turbine includes a third purpose: to improve the existing LCA model for Vestas wind turbines. These studies permitted Vestas to identify the environmental strengths and weakness of their product, which processes contributed most to the environmental impact and the consequences of improving those activities (e.g. increasing recycling of raw materials, etc.).

Due to the early stage of development of wave and tidal energy converters, studies were developed to obtain a first estimate of the carbon and energy payback period for these technologies [12], [9]. More extensive studies that included the contribution of processes and stages on carbon/energy intensity were carried out for Seagen [2] and Pelamis [3] while, for Wave Dragon, a wider range of impacts were evaluated [10].

Some other applications for performing LCA for marine energy technologies may be strategic planning and marketing when comparing with other technologies or competitors. The ISO Standards state that comparison is always challenging as it requires relatively deep analysis of methods. Baumann and Tillman [11] propose that the aim of the study may be formulated as a question posed to the LCA. Examples of such questions are the following: Where are the improvement possibilities in the life cycle of the product? Which are the activities in the life cycle that contribute the most to the environmental impact associated to this product? What would be the environmental consequences of changing certain processes in the life cycle in such a way? What would be the environmental consequences of using a secondary recycled raw material for this product, instead of the virgin material presently used? What is the environmentally preferable choice of products A, B and C used in application X? The aim of other relevant LCAs is to compare different renewable technologies ([13] and [14]), or the influence of external factors in the overall performance of the products, e.g., the location of the power plant [14].

2.1.1.1 Target Group

The target group to whom the LCA is directed is crucial when defining the goal of the study. Vestas's study [4] refers to two target groups: 1) the Danish turbine industry, including employees in Vestas' environment and improvement departments integrating environment into product improvement; 2) the interested public including the Danish Energy Authority to use the overall results as part of an assessment of the turbine's environmental characteristics. Vestas' follow up LCA [5] targets the following four groups: 1) Customers of Vestas; 2) Vestas itself; 3) Investors in Vestas Wind Systems A/S; 4) Other stakeholders, including energy authorities from countries with interest in renewable energy that should be able to use the overall results as part of an assessment of the environmental characteristics of Vestas turbines. In their review of the Vestas study Force Technology highlighted the importance of offering suitable information for the target group.

2.1.2 Scope of the study

The scope of the study refers to all the choices to make when performing an LCA. For a generic LCA these include [11]: 1) Options to model; 2) Initial flowchart; 3) Functional Unit; 4) Choice of impact categories and method of impact assessment; 5) Types of LCA; 6) System Boundaries; 6) Data quality requirements; 7) Assumptions and limitations. As regards system boundaries the following topics can also be developed: a) Boundaries in relation to natural systems; b) Geographical Boundaries; c) Time boundaries; d) Boundaries within technical systems. However, when performing an LCA for electricity production technologies the scope of the study can be defined by the following topics (following Vestas' and other LCA studies).

2.1.3 Functional Unit

The functional unit is the basis on which a product or processes impacts are reported. For electricity production plant the function unit is normally defined as 1kWh of electricity produced by the selected technology. It could also be defined as a single product manufactured (e.g. a wind turbine or wave energy converter) but referring all impacts per kWh enables comparison between different technologies or between different power plants of the same technology.

2.1.4 Choice of impact categories and method of impact assessment

At the beginning of the study it is necessary to define which environmental impacts to take into account. The ISO standard only gives three headlines for impact categories: resource use, ecological consequences and human health [6]. These must be interpreted in terms of more operational impact categories such as global warming, resource depletion (materials and energy) or land use. It should also be decided at this point how deep to go. Most studies choose to stop after the inventory analysis and interpret the inventory results directly: for example by CO_2 emissions and/or energy use [2], [3], [15]-[19]. Such a study is called life cycle inventory analysis instead of life cycle assessment.

ISO 14040 [6] defines the mandatory elements of a life cycle impact assessment (LCIA) as: impact category definition, classification and characterization. The LCA may finish with the interpretation of these results and it is only optional to follow from this point. There are ready-made impact assessment methods for the normalisation, grouping and weighting of the results as given by different methods, e.g., EDIP, Ecoindicator-99, etc. Each has slightly different impact categories. The main differences are found in the weighting methodologies.

Table 1 shows the impacts assessed in some of the LCAs reviewed for this report. It can be observed that most of the studies performed in marine and wind energy are focused on CO_2 emissions and energy use during device lifetime. Results on the evaluation of carbon and energy impacts show very good performance of wave and tidal against conventional power plants and other renewables [2], [3]. To date, only one paper [10] on the Wave Dragon has included most of the impacts; however this study is very generic and uses many assumptions due to the early stage of technology, so further work should be addressed in this field. However, experience from wind LCA studies and the similarities of this technology with marine devices imply that results for wider impacts may be negligible when compared to conventional power plants or other renewables such as biomass or solar PV (e.g. eutrophication, acidification, etc.) as shown in [4], [5], [8]. However, wind energy's impact on waste is found to be larger than most technologies and it is supposed to be even higher for wave at this early stage [20].

2.1.5 System Boundaries

System boundary definition and allocation are decided during the goal and scope definition but may be adapted during the inventory analysis. Boundaries can be defined in different dimensions (physical, time, geographical, etc.), but for renewable energy technologies they can be described in the following points.

Table 1 Impacts assessed in LCA studies reviewed.

Impact Categories	LCA on Wave	LCA on Tidal	LCA on Wind	LCA on Other Energies
Global warming[1]	[3], [10], [12]	[2]	[4], [5], [8], [16], [17]	[15], [18]
Ozone-depletion	[10]		[4], [5]	
Acidification	[10]		[4], [5], [8]	[15]
Eutrophication	[10]		[4], [5], [8]	[15]
Photochemical smog	[10]		[4], [5], [8]	
Human toxicity	[10]		[4], [5]	
Ecotoxicity	[10]		[4], [5], [8]	
Abiotic resource depletion			[8]	[15]
Biotic resource Depletion				
Energy Intensity/Payback[2]	[3], [10], [12]	[2]	[4], [5], [8], [16], [17]	[15], [18]
Bulk waste	[10], [19][3]		[4], [5]	[15]
Slag and ashes	[10]		[4], [5]	
Hazardous waste	[10]		[4], [5]	
Radioactive waste	[10]		[4], [5]	
Land use				

2.1.5.1 Life cycle stages

All processes from raw material extraction (including energy) to end of life and disposal should be included when performing an LCA. For electricity production technologies the life cycle is normally separated in four stages (Figure 2).

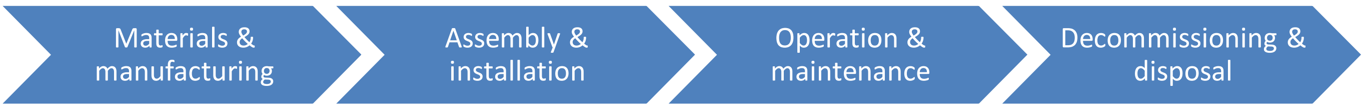


Figure 2 Life Cycle Stage for electricity production plants.

Studies for Seagen [2] and Pelamis [3] use the scheme showed in Figure 2. Vestas maintain the same four stages calling the second stage 2 (assembly & installation) as transport and erection, and stage 4 as dismantling and scrapping. However other studies may aggregate the life cycle in other stages. As an example, the Wave Dragon LCA cited in the NEEDs project report [10] allocates the process in only three stages: production (including manufacturing and transport), operation (including maintenance) and disposal (include dismantling and transport). All the before mentioned studies cover the whole life cycle but some differences in the life stage definition may provoke changes in the allocation of impacts within some life stages. In the disposal stage: waste can follow different paths: typically incineration, landfill, recycling or a combination of them. As mentioned later the rate of recycling has great impact on the overall performance of the products. Figure 3 shows the detailed life cycle defined for Pelamis. In that study only energy input is considered since the goal of the study was evaluating the energy and carbon performance of the device.

[1] Most of the studies do not perform impact assessment but indicate at the inventory level the CO_2 emissions per kWh.
[2] Most of the studies only focus on the energy use at the inventory level in terms of MJ/kWh.
[3] This study makes a gross estimate of the iron ore use for wave and wind devices.

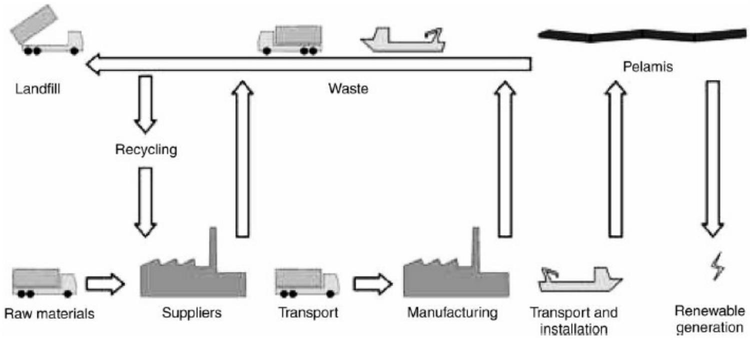


Figure 3 Detailed product life cycle for Pelamis [3].

2.1.5.2 Physical Boundaries

It is very important to define the physical boundaries of the system, especially when comparing different electricity production technologies. Figure 4 shows the system boundaries for an offshore wind farm comprising Vestas V90-3.0 MW turbines erected on monopiles 14km from the coast. The 32kV cables comprising the grid connected to the offshore transformer station are included in the study but the 150kV external sea cable, transmission station and the external land cable to the onshore transformer station are not.

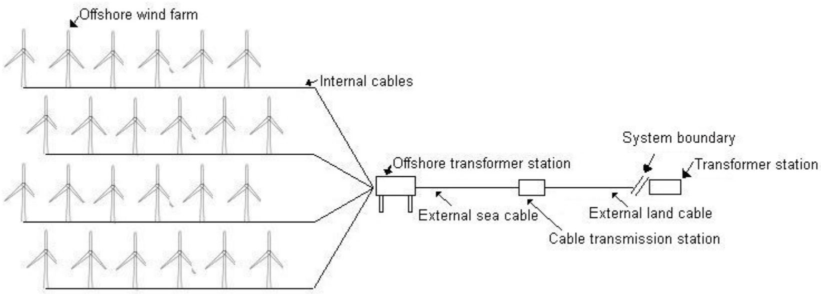


Figure 4 Sketch of offshore wind power plant structure with system boundary for the LCA [5].

This approach seems to be best as it includes all the elements needed to connect a power plant to the national grid at the transformer station available closer to the location of the plant. However, studies performed on marine energy technologies to date include smaller boundaries. The modelling of the electricity production for Wave Dragon [10] included a farm of 23 devices of 7MW each, the internal cables, transformer station, marine transmission cable and a cable transmission station, but not the external land cable to the national grid transformer. The Pelamis and Seagen studies [2], [3] encompassed only one device, its moorings and umbilical sub-sea transmission cable (see Figure 5) with all downstream elements of the electricity transmission system outside the scope of the LCA. This was to allow the nascent technology to be seen 'stand-alone' but follow-up studies will offer a farm analysis to account for all the environmental impacts of installing these devices. When comparing different technologies it is sensible to include some of the grid infrastructure particularly where different technologies imply different connection infrastructure.

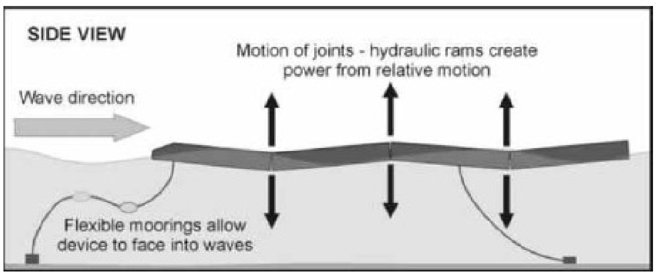


Figure 5 System boundaries for Pelamis LCA [3].

2.1.5.3 Geographical Boundaries

Geography matters in LCA for the following reasons [11]: 1) Different parts of a life cycle occur in different parts of the world; 2) Infrastructure such as electricity production, waste management and transport systems vary from one region to another; 3) The sensitivity of the environment to different pollutants varies in different geographical areas. When studying renewable energy technologies, it is very important to indicate the data sources in terms of location and time period, the level of detail and assumptions adopted in the study, especially when comparing data from different studies. When gathering different LCA performed on renewable energies data is obtained from different national databases or at a European level. The studies present similar methodology but different levels of detail and regional data sources. Especially important is the location of the production process and data related to the national energy mix[4]. For instance, three of the studies correspond to power plants with construction and installation in Germany, United Kingdom and European Level. These three regions present energy mixes with a CO_2 intensity of 566, 540 and 548 gCO_2eq/kWh respectively. Two studies have been found from Denmark, one is supposed to be done with the national energy mix which should be more carbon intensive than the average European or German mix (no Nuclear power and high share of coal fired plants in Denmark). Vestas claim to use 65% of their electricity from neutral CO_2 sources, which will have a positive impact on the embodied CO_2 of their products: this is a reasonable basis if generation is on site but may be open to question for offsite energy sources. These differences will have an impact on the CO_2 intensity of the technologies. Table 2 shows typical values of the European energy mixes but will rapidly vary with the massive introduction of new technologies as renewables or nuclear. The geographical location of the production and installation of the devices may also have different impacts on the local environment, biodiversity or local acceptance, among others.

Table 2 Typical values of CO_2 intensity for European energy.

Country/Region	Year	Carbon Intensity (gCO_2eq/kWh)	References
EU		548	[5]
Germany		566	[15]
UK		540	[11]

2.1.5.4 Lifetime and Production

Results from the LCA are expressed in terms of the kWh functional unit. Thus the lifetime of power plant and transmission components will affect the results of the environmental analysis as explained. Almost all studies on renewable energy plants assume that a plant lifetime of 20 years, although in some cases it may exceed this value. The Wave Dragon [10] LCA assumes a lifetime of 50 years which inherently reduces the impacts by 2.5 times relative to an analysis assuming a 20 year life time. It is appropriate to use a longer life time if the technology is credibly designed for it and not to artificially overstate environmental performance. Production values depend on the type of energy and selected technology, but also on the location of the plant, the state of technology development, and lifetime. The literature does not describe assumptions on changes in performance over the lifetime of the plant and it could have an important role on the overall performance. For instance, warranties on solar PV panels assure a decrease on efficiency of no more than 1% per year: this should be accounted for or applied as an average annual production value. As mentioned in the previous section, it is also very important to state the date of the data used for the inventory analysis as technology, processes and materials change greatly in time.

2.1.6 Data Quality

Baumann and Tillman [11] state that depending on which data is used, the model to be built will give different views of reality. Different ambitions concerning data quality will also lead to different workloads when carrying out the study but of course also to different reliability in the results. Deciding on quality requirements is thus an important activity during the goal and scope definition. For instance, data quality may not be so severe when conducting a 'whole sector' assessment but may be more rigorous to enable a specific model or technology to obtain a green certificate. The ISO standard lists different aspects of data quality (most of them previously mentioned): 1) Time-related coverage; 2) Geographical coverage; 3) Technology coverage; 4) Completeness; 5) Representativeness; 6) Precision; 7) Consistency; 8) Reproducibility.

2.1.7 Critical Review Process

It may be important in terms of validating the study (especially when performing LCA for the first time) that the study results are communicated to the public and a third party with experience performs a critical review of the process [5]. ISO compliance requires such a review.

2.1.8 Software and Databases

Several software and databases are freely available or licensed for a fee. Several commercial databases have large datasets and the most complete at European level is Ecoinvent. EDIP has also been used but it accounts only for Denmark. The most heavily used commercial software tools are Gabi and SimaPro. A summary of database and software available is included in section 3.

[4] A specific supply mix can be used only if the origin of electricity can be guaranteed (by the producer), otherwise a national country mix should be preferred.

2.2 INVENTORY ANALYSIS

2.2.1 Construction of the Flow Chart

The construction and implementation of the material and process flow model is done in the inventory analysis stage. Flow models can be very large and complex to perform a rigorous LCA analysis. Depending on the goal of the study it can be chosen to perform a detailed flow model including all inputs (raw materials and energy), processes and outputs. However in some cases it may be better to perform a simplified analysis with several assumptions, with all assumptions clearly justified. An example of flow chart is shown in Figure 6. Each of the boxes included in the flow chart correspond to a specific process with several inputs, normally in terms of raw materials and energy but sometimes ancillary inputs and other physical inputs may be introduced (e.g. "land use"). From this process several outputs will be obtained, normally products (and by products if the case) and emissions to air, water and land. Other environmental aspects could be considered as outputs (e.g. "noise") (Figure 7).

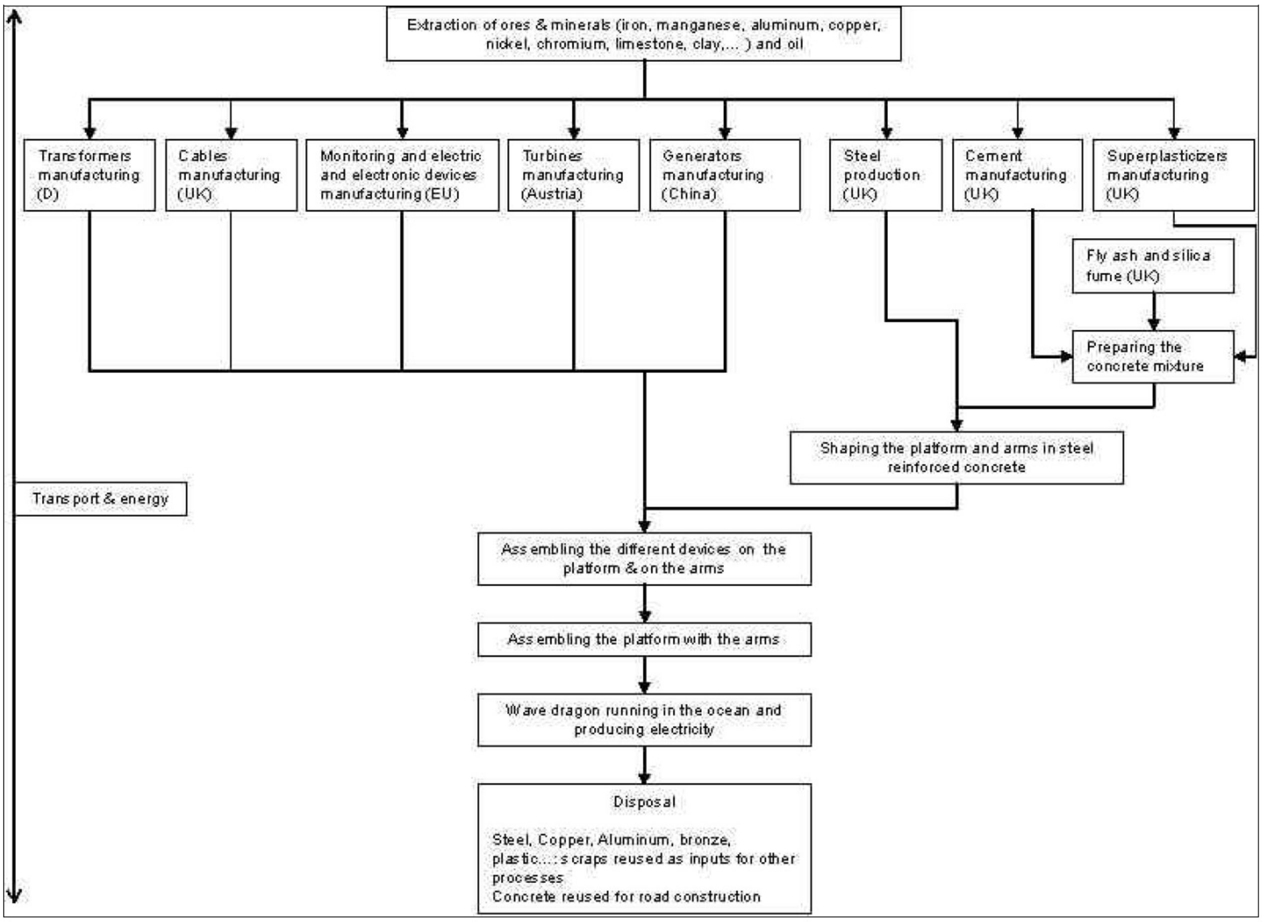


Figure 6 Flow chart of the life cycle of Wave Dragon [10].

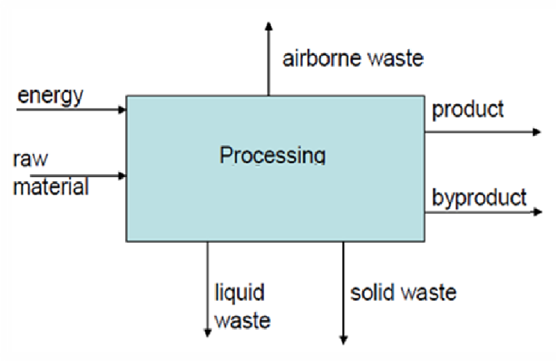


Figure 7 Processes included in LCA.

2.2.2 Data Collection

When performing LCA, the first intention should be to collect the most accurate data for inputs (raw materials including energy) used during the whole life cycle. However, this may be very time consuming and, depending on the goal and scope of the study and the amount of components of the system, simplified flows may be used carefully. For example, many of the LCAs on renewable energy only focus on the energy and CO_2 intensity of the processes, so material flows may only be included to perform these evaluations but not used to estimate, e.g., the solid wastes of the processing. As such, when collecting data it is important to consider the following points:

2.2.2.1 Data sources

The information about various materials is usually obtained from different databases (see section 3), normally preferred at national level due to geographical differences, e.g. in CO_2 intensity of the energy mix. If not available, European average data can be used [3], [15]. Some of the software available already includes large databases. In cases where LCA data is not available or the existing data was inadequate, new data can be collected through suppliers and other LCA studies. In some cases, it is necessary to make assumptions about the materials which should be described in the study [4], [5].

2.2.2.2 Planning for data collection

Before sourcing data it is important to address several issues First, it is important to identify which activities are the most important so more effort and detail can be targeted. Vestas [4] concluded that for wind turbines, the most significant environmental impacts arise during manufacturing and final disposal of the turbines, with the operational stage contributing little to environmental impacts. Therefore, data collection was focused on procuring data for the production and disposal stages. Vestas differentiated between 'first' and 'second' level information : first level information is materials use in Vestas factories like Prepreg for blades and steel for towers; second level information is for processes like resources, materials and consumables used by suppliers including energy used in the manufacture of steel profiles and content of substances in Prepreg. Vestas; aim was to cover 95% of the first level information and prioritising the important information for the second. The LCA performed on Pelamis [3] states that the primary focus of the study was to collect the most accurate data available for the manufacturing stage of the life cycle. Where complete data for a component was difficult to obtain, alternative sources were used including previous LCA studies. The vast majority of the Pelamis device was analysed directly in terms of its materials, processing, and mass. However, with the electrical and electronic systems comprising large numbers of smaller components, it was necessary to use capital cost methodologies to estimate energy and CO_2 emissions. Given the expected modest contribution of these systems to overall embodied energy and carbon, this approach was appropriate but precluded the presentation of a complete materials and mass classification for the device; this is clearly an area for further work. Then it is also important to think about which activities are site specific and activities for which average data is preferred. Finally, before approaching suppliers it is important to be prepared regarding what data is required, the form in which it is to be collected and how to handle confidentiality [11].

2.2.2.3 Validation of data

ISO 14040 [6] requires that a check of the validity of the data is performed. It can be done by comparison with other sources, mass and energy balances, etc.

2.2.3 Calculation Procedure

Following Baumann and Tillmann's guide to LCA [11], after drawing the flowchart and collecting the data, the calculation can finally be done. LCA software tools make these calculations automatically and are very useful for large amounts of data. However, for small LCAs it may be as easy to solve the system of equations by hand and then use a spreadsheet program for the rest of the calculations. It should be addressed through the following steps:

1. *Normalise* data for all the activities for which data have been collected, i.e. relate the other inputs and outputs of that activity to the product, in this case kWh of energy generation. In theory this is a simple operation but in practice mistakes are often made and errors introduced in this step, e.g. when converting units.
2. Calculate the flows *linking* the activities in the flowchart, using the flow representing the functional unit as a reference. This is done by setting up relationships between inflows and outflows ("mass balances") for the individual activities in the low chart and solving the resulting equation system. One of the equations is the one defining the reference flow.
3. Calculate the flows *passing the system boundary*, again related to the functional unit. This is a simple operation, since step 2 has given the size of the linking flows and step 1 the relation between different flows for each activity.
4. *Sum up* the resource use and emissions to the environment for the whole system.
5. *Document* the calculations.

Figure 8 shows the results of the inventory analysis for the Sway floating wind farm. It can be observed that there is a lot of information to analyse. A complete analysis may produce a lot more data so the impact assessment methods permit categorisation of the data to facilitate understanding (see section 2.3).

2.2.3.1 Allocation

As marine energy generators typically only produce electricity and no heat, there is no need to allocate between more products. This simplifies the inventory as it is all related to one product in terms of kWh of electricity generated. However, allocation of by-products and other aspects within materials, processes and transport must be considered up front to ensure appropriate treatment.

Table 3
Aggregated inventory data for the process "Sway floating wind power plant 5 M_W"[a]

Material	Amount/power plant	Unit	Amount/1 MJ	Unit
Steel, low alloyed	1.41E+06	kg	8.47E−04	kg
Steel, high alloyed[b]	5.25E+03	kg	3.17E−06	kg
Gravel	3.23E+06	kg	1.94E−03	kg
Copper	5.85E+04	kg	3.53E−05	kg
Lubricating oil	7.51E+04	kg	4.53E−05	kg
Aluminum	2.25E+03	kg	1.36E−06	kg
Chromium steel	1.35E+05	kg	8.17E−05	kg
Glass fiber	5.21E+04	kg	3.14E−05	kg
Lead	1.29E+04	kg	7.78E−06	kg
Polyethylene	1.45E+04	kg	8.72E−06	kg
Cast iron	6.91E+04	kg	4.17E−05	kg
Polyvinyl chloride	9.22E+03	kg	5.56E−06	kg
Electro steel[b]	4.75E+03	kg	2.86E−06	kg
Epoxy resin[b]	1.44E+03	kg	8.67E−07	kg
Logs[b] (wood)	3.60E+02	kg	2.17E−07	kg
Synthetic rubber	2.63E+02	kg	1.58E−07	kg
Ceramics[b]	5.39E+01	kg	3.25E−08	kg
Tin	1.31E+00	kg	7.92E−10	kg
Transport				
Truck transport (lorry 40 tons)	8.76E+05	tkm	5.28E−04	tkm
Transport barge	3.60E+06	tkm	2.17E−03	tkm
Train transport	5.81E+05	tkm	3.50E−04	tkm
Transport helicopter (time)	7.00E+02	h	4.22E−07	h
Transport helicopter (take off and land)	1.00E+02	p	6.03E−08	p
Energy				
Electricity	1.77E+05	kWh	1.07E−04	kWh
Oil	2.26E+04	L	1.36E−05	L
Diesel	9.22E+02	MJ	5.56E−07	MJ
Electricity from oil	4.70E+02	kWh	2.83E−07	kWh
Processing				
Sheet rolling steel	1.08E+06	kg	6.53E−04	kg
Sheet rolling aluminum	2.22E+03	kg	1.34E−06	kg
Sheet rolling chromium steel	1.35E+05	kg	8.17E−05	kg
Welding arc steel	7.51E+03	m	4.53E−06	m
Wire drawing copper	8.29E+03	kg	5.00E−06	kg
Section bar rolling	1.12E+05	kg	6.72E−05	kg
Avoided products				
Pig iron	9.22E+05	kg	5.56E−04	kg
Copper	2.10E+04	kg	1.27E−05	kg
Gravel	2.10E+06	kg	1.27E−03	kg
Waste treatment processes				
Disposal, polyvinyl chloride, municipal incineration	3.69E+03	kg	2.23E−06	kg
Disposal, used mineral oil, to hazardous waste incineration	3.00E+04	kg	1.81E−05	kg
Disposal, glass, to inert material landfill	1.22E+05	kg	7.36E−05	kg
Disposal, plastics, to municipal incineration	3.82E+04	kg	2.30E−05	kg
Disposal, polyethylene, municipal incineration	7.10E+01	kg	4.28E−08	kg
Emissions[c]				
CO_2	4.98E+05	kg	3.00E−04	kg
CH_4	1.55E+03	kg	9.34E−07	kg
N_2O	1.47E+02	kg	8.86E−08	kg
SO_2	1.11E+03	kg	6.71E−07	kg
NO_x	5.00E+03	kg	3.01E−06	kg
NMVOC	1.50E+03	kg	9.04E−07	kg
CO	1.63E+03	kg	9.80E−07	kg
NH_3	6.93E+01	kg	4.17E−08	kg
PM10	2.13E+02	kg	1.28E−07	kg
PM2.5	1.83E+02	kg	1.10E−07	kg
Lead	1.33E−01	kg	7.99E−11	kg
Cadmium	8.75E−03	kg	5.27E−12	kg
Mercury	1.50E−02	kg	9.04E−12	kg
Arsenic	5.00E−02	kg	3.01E−11	kg
Chromium	2.03E−01	kg	1.22E−10	kg
Copper	1.16E−01	kg	6.99E−11	kg
PAH, polycyclic aromatic hydrocarbons	4.50E−02	kg	2.71E−11	kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.00E−07	kg	2.41E−16	kg

[a] All processes and materials which are included within the system boundaries of LCA study are listed in this table.
[b] These processes are taken from the ETH-ESU database [18].
[c] These emissions are derived from input-output table, which is used in the inventory analysis for cable production process.

Figure 8 Aggregated inventory data for the process "Sway floating wind power plant 5 MW" [8].

2.2.3.2 Recycling

Most current marine renewable technologies comprise large metallic structures and thus the ability to recycle material can have an impact on the LCA results. The use of recycled – or secondary – materials in place of primary – or virgin – materials tends to have lower environmental impacts. As such, some of these benefits can be attributed to recycling in the form of a 'credit' that offsets some of the impacts associated with use of primary materials. There are, however, several different methods to assess the impact of recycling on the impact of the marine energy device. The authors of the University of Bath's Inventory of Carbon and Energy (ICE) identify three principal methods that can be applied to recycling [21]. Although aimed at users of the ICE inventory it has wider applicability. The first method is the substitution method whereby any recycled content of the stock materials is disregarded with figures taken for virgin materials only. All of the credit associated with recycling waste products is allocated directly to the turbine. A problem with this method is that it highlights the potential for reducing the embodied energy and CO_2 by recycling the turbine at its end-of-life, and disregards any potential benefit of using a high proportion of recycled material in the manufacture of the turbine. The recycled content method is used in the ICE to generate typical cradle-to-grave data. This method allocates all of the credit for using recycled materials to the product, but means that no credit can be taken for recycling materials at their end-of-life. The 50:50 method is a compromise method suggested as a way of taking into account both the recycled content of the materials used in manufacture, and the potential credit of recycling the waste at the end-of-life [21]. This is achieved by simply allocating 50% of the credit from the recycled content of the materials selected for manufacture and 50% of the credit from recycling waste to the product in question. It is considered [21] the most robust method, as it takes into account both design and decommissioning decisions. It is important to note that the way in which recycling processes are treated is important in order to avoid "double-counting", where the credit for recycling a material is allocated to both the primary and secondary materials, and therefore the benefit is counted twice.

Moreover benefits cannot be accounted twice: if a module used in the LCA already contains some recycled material (like steel), the recyclability rate has to be applied only to the non-recycled part.

In their LCAs Vestas consider a recycling rate of 90% for steel in their wind turbines [4], [5]. Due to the positive impact of recyclability they also performed a sensitivity analysis for increasing the rate to 95% and 100% with large improvement in environmental performance (see Figure 9). In the case of marine energy technologies it may be still too early to know the likely rate of recycling but offshore wind experience can serve as a benchmark for wave and tidal as they share similarities. Following this, the detailed LCAs on Seagen (tidal current) [2] and Pelamis (wave) [3] consider the same 90% rate for steel recycling.

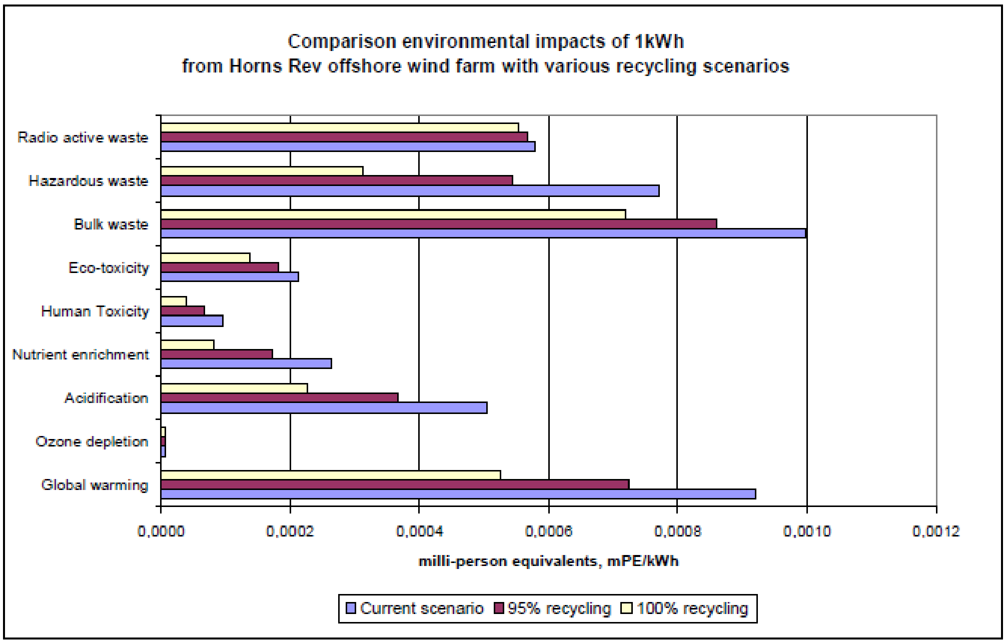


Figure 9 Comparison environmental impacts of 1kWh from Horns Rev offshore wind farm with various recycling scenarios.

2.3 IMPACT ASSESSMENT

The *life cycle impact assessment* (LCIA) phase aims to describe the environmental consequences of the loads quantified in the inventory analysis. The impact assessment is achieved by translating the environmental loads from the inventory results into environmental impacts, such as global warming, acidification, ozone depletion, etc. There are several reasons for this translation. For many, it is easier to relate to, for example, acidification consequences rather than SO_2 emissions. The purpose is thus to make the results more environmentally relevant, comprehensible, and easier to communicate. Another purpose is to improve the readability of the results. However, some impact indicators, particularly ecotoxicity and toxicity indicators are not consensual since weighting different substances emitted in different places is difficult due to the phenomena complexity.

The number of inventory results parameters can range from 50 to 200 or more but through LCIA, the number of parameters can be reduced to approximately 15 by grouping the environmental loads of the inventory results into environmental impact categories. It is possible to develop a single impact measure (Figure 10) by weighting across the impact categories, although this is not ISO compliant.

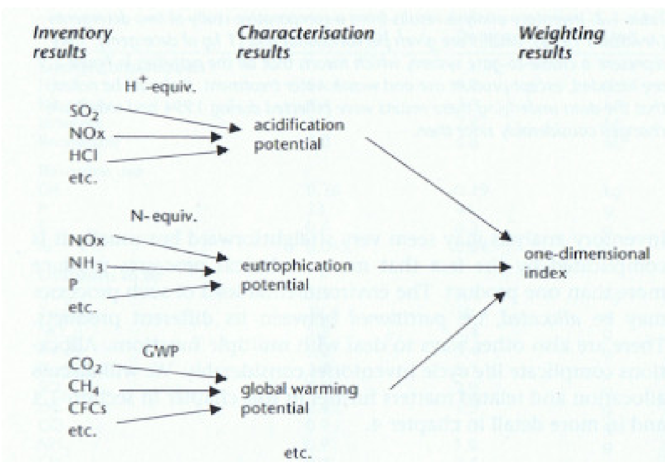


Figure 10 Illustration of the stepwise aggregation of information in LCIA [11].

There are several methods to assess the life cycle impact, The most commonly used for renewable energy in Europe are EDIP (originally aimed at Denmark) [4], [9] and Ecoindicator-99 (aimed at European level [14]. Other methods like CML for Germany [8] or EPA are available. All these methods converge to the same process defined by the ISO standard. The large number of inventory results is grouped in different impacts categories through the characterisation of the results that cause a specific impact. For example, emissions of CO_2, CH_4, CFCs and others contribute to the GHG effect with different weights defined according to their global warming potential. However, the different methods differ in the way they present and weight the different impacts.

Figure 11 presents commonly-used life cycle impact categories and Figure 12 presents the most significant impacts from energy production technologies based on work for the World Energy Council [22]. Similarities between wind, and wave and tidal technologies suggests that marine energy technologies will have impacts on sea use, visual impact and/or noise compared to other production options. However, wind energy and therefore marine and tidal will have low impact in resource depletion, greenhouse effect, acidification or eutrophication [22].

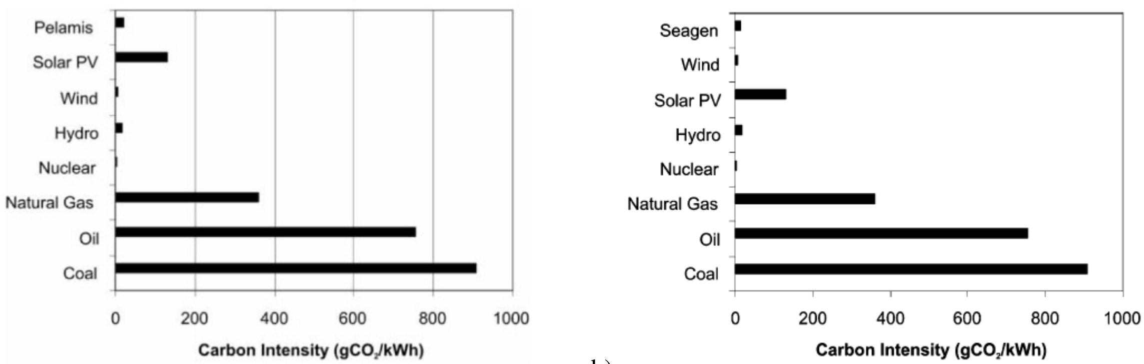
Impact Category	Scale	Relevant LCI Data	Common Characterisation Factor	Description of Characterisation Factor
Global Warming	Global	Carbon Dioxide (CO_2)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents
		Nitrous Oxide (N_2O)		Note: Global warming potentials can be 50, 100 or 500-year potentials
		Methane (CH_4)		
		Chlorofluorocarbons (CFCs)		
		Hydrochlorofluorocarbons (HCFCs)		
		Methyl Bromide (CH_3Br)		
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents
		Hydrochlorofluorocarbons (HCFCs)		
		Halons		
		Methyl Bromide (CH_3Br)		
Acidification	Regional	Sulphur Oxides (SOx)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents
	Local	Nitrogen Oxides (NOx)		
		Hydrochloric Acid (HCL)		
		Hydrofluoric Acid (HF)		
		Ammonia (NH_4)		
Eutrophication	Local	Phosphate (PO_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents
		Nitrogen Oxide (NO)		
		Nitrogen Dioxide (NO_2)		
		Nitrates		
		Ammonia (NH_4)		
Photochemical Smog	Local	Non-methane volatile organic compounds (NMVOC)	Photochemical Oxidant Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents
Human Health	Global	Total releases to air, water and soil.	LC_{50}	Converts LC_{50} data to equivalents
	Regional			
	Local			
Resource Depletion	Global	Quantity of minerals used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve
	Regional	Quantity of fossil fuels used		
	Local			
Land Use	Global	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density

Figure 11 Commonly used life cycle impact categories [23].

Type of impact	Combustion based				Nuclear	Hydro	Wind	Solar
	Coal	Oil	Gas	Biomass				
Resource depletion	X	X	X		X			
Land use, visual impact	(X)			X		X	X	X
Watercourse regulation						X		
Thermal releases	X	X	X	X	X			
Noise							X	
Radiation					X			
Air quality	X	X	X	X				
Acidification	X	X	X	X				
Eutrophication	X	X	X	X				
Greenhouse effect	X	X	X	X				

Figure 12 The most significant environmental impacts of energy production forms [23].

Studies performed on marine energy technologies have been mainly focused on the greenhouse effect and corroborate the low impact of these technologies. These include estimates of the carbon intensity of around 15 gCO_2/kWh for tidal (Seagen) [2], 23 gCO_2/kWh for the Pelamis wave device [3] and approximately 50 gCO_2/kWh for an early stage design for the Oyster wave energy device (unpublished report). These compare very favourably to far higher amounts for fossil fuels of 400-1000 gCO_2/kWh (Figure 13). The value is also strongly correlated to the amount of energy used during the whole life cycle and thus contributes to low energy resource depletion.



a) b)

Figure 13 Comparison of carbon intensity from several energy sources [2], [3].

However, another study performed on several renewable technologies by Pehnt [15] shows that in terms of iron ore requirements, wind energy (as well as solar PV, geothermal and other renewables) have more impact than conventional production plants. Figure 14 shows several of these wider impacts across different energy technologies. Based on data from Pelamis [3], Tavares and Raventos [19] estimate the iron ore requirements for wave energy to be around 30% higher than wind. The environmental impact may not be significant as the available resource of iron is extremely large, but it points out a good direction for improvement in cost reduction by reducing or changing the structural material. The impact of changing the materials is discussed later.

To date, only one paper has examined wider impact categories for marine energy technologies. The study of the Wave Dragon [10] shows that electricity production from Wave Dragon avoids consumption of various fossil fuels and contributions to other environmental impacts like emissions of greenhouse gases, bulk waste and dangerous chemicals (Figure 15). The paper offers only limited information on the assumptions adopted and it assumes a very long life time of 50 years.

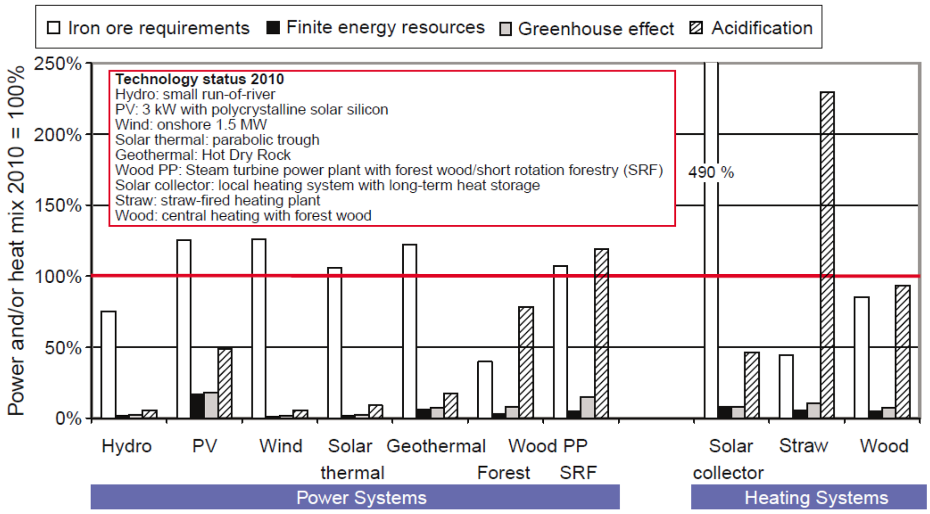


Figure 14 Normalized LCA of selected renewable energy systems for four impact categories [15].

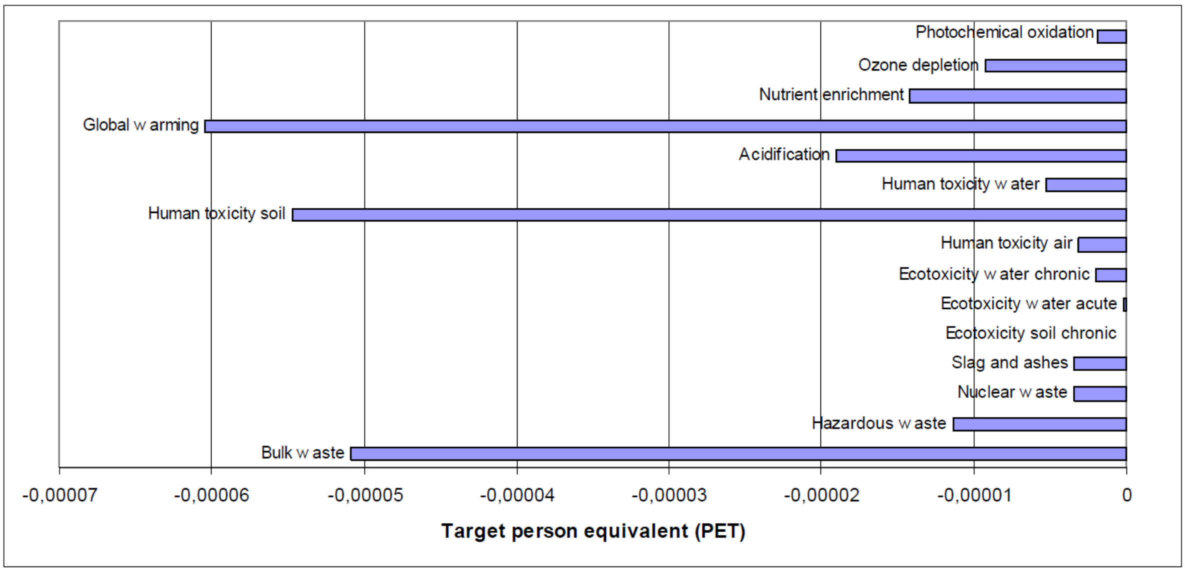


Figure 15 Weighted environmental impact potentials for the whole life cycle [10] (calculated in accordance to the EDIP method).

2.4 Interpretation and Presentation of Results

2.4.1 Units and normalization for results presentation and interpretation

There are different approaches to presenting the results depending on the preference of the user. The Danish EDIP method normalizes the impact results as 'target person equivalent' (PET). The results reflect what 1 kWh power produced from the wind farms through their lifetime contribute to an average Danish citizen's total environmental impact. (see Figure 9 and Figure 14). The 'person-equivalent' approach can be difficult to translate to other regions and so expressing the results in physical units such as CO_2 equivalent for a specific impact facilitates comparability. Most studies performed on marine and wind devices are focused on GHG emissions and show results in terms of CO_2 equivalent units per kWh sold ($CO_{2\text{-eq}}$/kWh) as well as the payback period necessary to produce the energy consumed during the whole life (or the CO_2 emitted and avoided). Table 3 summarises results on carbon intensity and payback periods for different marine and other electricity production technologies.

It can also be very useful to normalize the results by comparing to reference technologies. For example, Pehnt [15] normalises results for generating systems relative to the German 2010 electricity mix, with a value higher than 100% suggesting relevant environmental impacts are detrimental relative to the mix and vice versa. This normalization serves two purposes: (1) environmental advantages and disadvantages of the electricity consumption can be identified easily; and (2) different environmental impacts can be represented in one diagram.

Table 3 Carbon intensity and payback periods for electricity production technologies

Technology	Carbon Intensity (gCO_2eq/kWh)	Energy Payback (months)	Carbon Payback (months)	Ref.
Pelamis WEC	22.9	20	13	[3]
Pelamis WEC	25-50		20	[12]
Wave Dragon	13	29		[10]
Seagen tidal current turbine	15	15	8	[2]
V90 onshore wind turbine	4.64	6.6		[5]
V90 offshore wind turbine	5.23	6.8		[5]
Sway floating wind turbine	11.5			[8]
2.5MW offshore wind turbine	9			[15]
3.1MW hydropower	10			[15]
Generic Solar PV	104			[15]
Solar Thermal	14			[15]
Geothermal	41			[15]
European Electricity Mix	548			[5]

Tavares and Raventos [19] expend the analysis of Pehnt [15] by introducing LCA data for wave energy to compare against other technologies. Figure 16 and Figure 17 show the energy and carbon performance for wave is among the best of the renewable technologies along with large hydro and solar thermal. The energy intensity of wind is only 8% of that of Solar PV intensity while wave intensity is around 15% of PV. In terms of carbon intensity the same comparison represents around 11 and 24% respectively for wind and wave. Results from Pehnt [16] show that wave and wind energy are the most iron ore intensive technologies among renewables (wave iron ore intensity estimated from Pelamis' steel weight and has been added to the results of this study [19]). Comparing results against the European Mix, the carbon and energy intensity of wave and wind are insignificant, generating only 1 to 4% of the Mix levels. All renewable technologies have lower impacts in terms of carbon and energy. However, it can be observed that wind, wave, solar thermal and PV and geothermal technologies are more iron ore intensive than the overall EU Power Mix (EU27 mix in 2006: 55% conventional thermal, 30% nuclear, 16% renewables, 1% others).

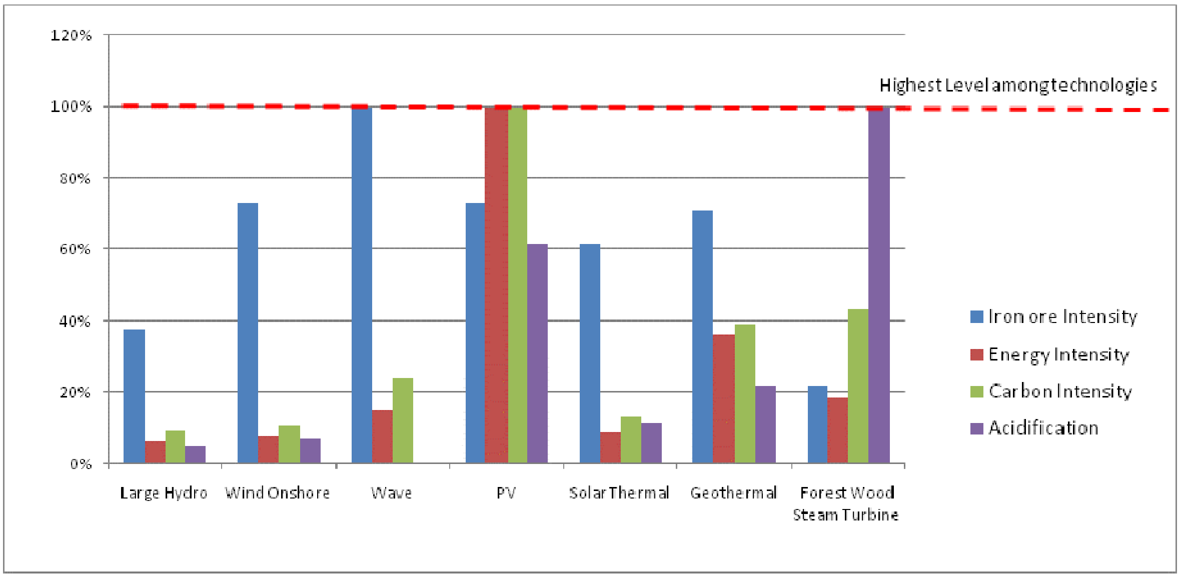


Figure 16 Energy, Iron ore, CO_2 and acidification intensities compared with the worst performance [19].

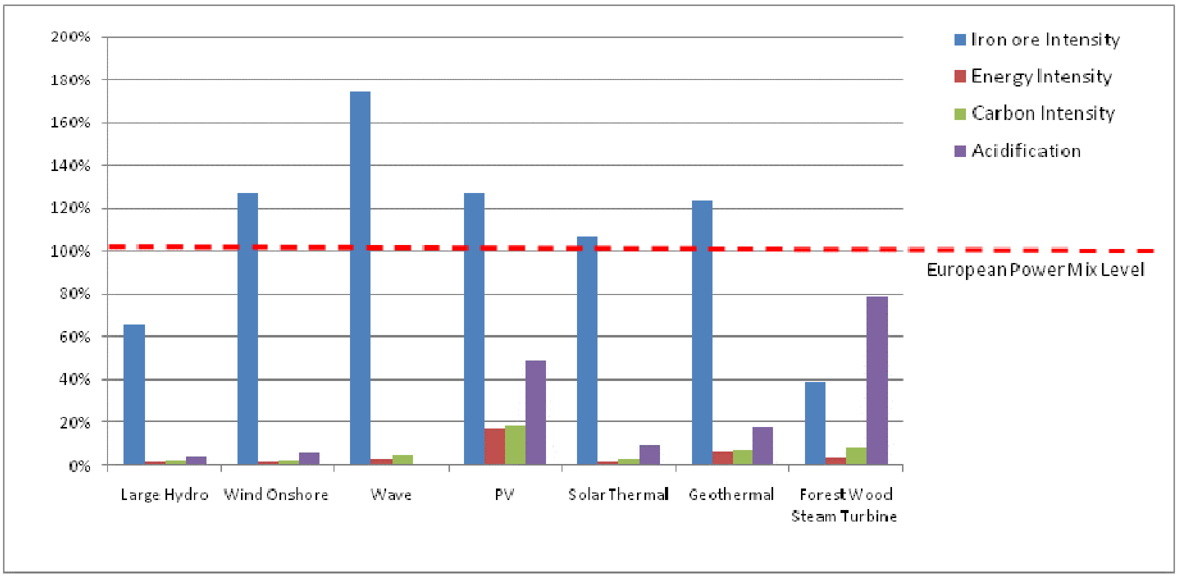


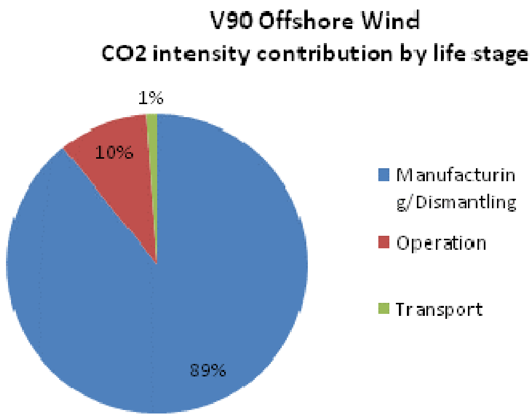
Figure 17 Energy and CO_2 intensities compared with the European Power Mix level [19].

2.4.2 Allocating the environmental impacts

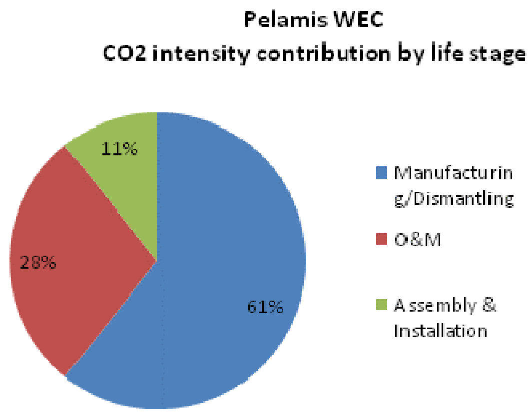
LCA permits the impacts to be broken down by process, material, life stage, etc. This information is valuable for developers, promoters and operators trying to optimize the environmental performance of each process in the life cycle.

2.4.2.1 Breaking down the impacts into life stages

Figure 18 presents the carbon distribution for an offshore Vestas V90 wind turbine and the Pelamis wave converter. Manufacturing and dismantling are the major carbon emitting phases of their life cycles, mainly due to material use. Operation and maintenance in an offshore location may also have an important contribution. However, some difference can be observed from the comparison between wind offshore and wave, probably due to the different allocation of specific processes in different phases. One important aspect to point out is the negative embodied energy and CO_2 of the disposal phase. This is due to the high rate of recycling (typical steel recycling rate is 90%) which credits part of the energy and carbon needed for the manufacturing of the materials. The use of different recycling rates will have a very significant impact on their environmental performance.



a)



b)

Figure 18 Carbon distribution for a) offshore wind turbine and b) Pelamis wave converter [3], [5], [19].

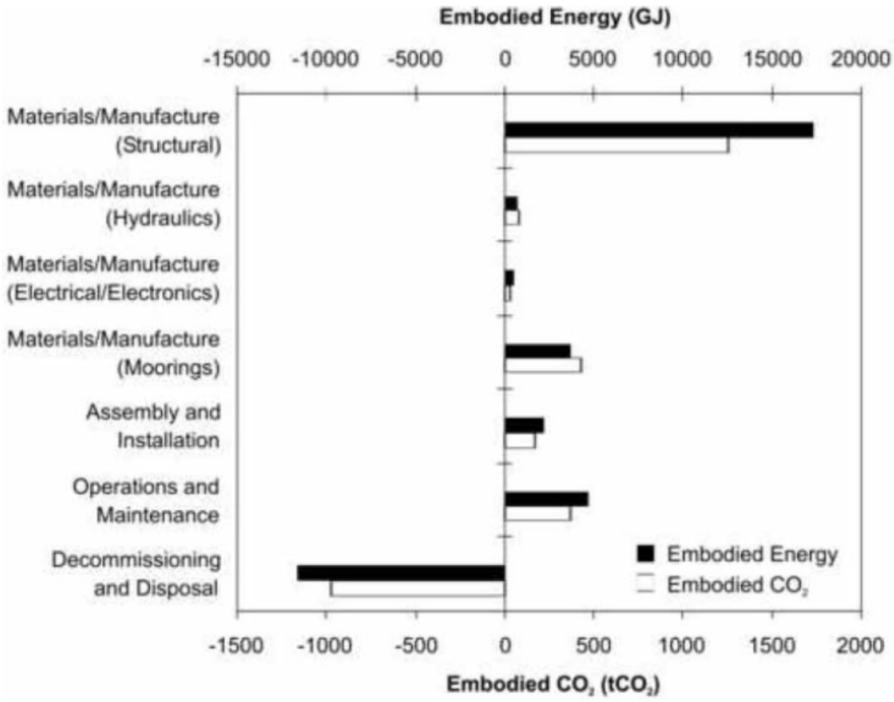


Figure 19 Embodied energy and CO_2 by life cycle stage for Pelamis [3].

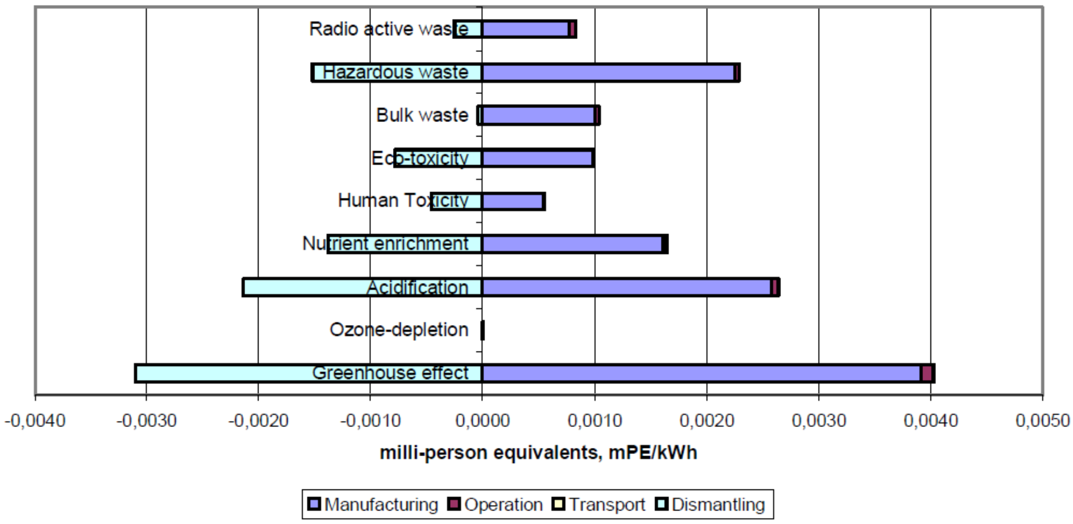


Figure 20 Environmental impacts of 1kWh from Horns Rev offshore wind farm divided into stages [4]

2.4.2.2 Breaking down the impacts into components

It can also be very important when optimizing the environmental performance or the costs of a specific device to break them down by component. Figure 21 shows the embodied energy and CO_2 of the main structural components of the Pelamis wave device [3]. This study also shows the embodied energy and CO_2 of other components as shown in Figure 19. The moorings are also intensive in energy and CO_2 while other components such as the hydraulics and electronics have a more modest contribution. This type of information can be very useful when defining the depth of the study. Results are also broken down into different materials, processes in manufacturing, activities, etc.

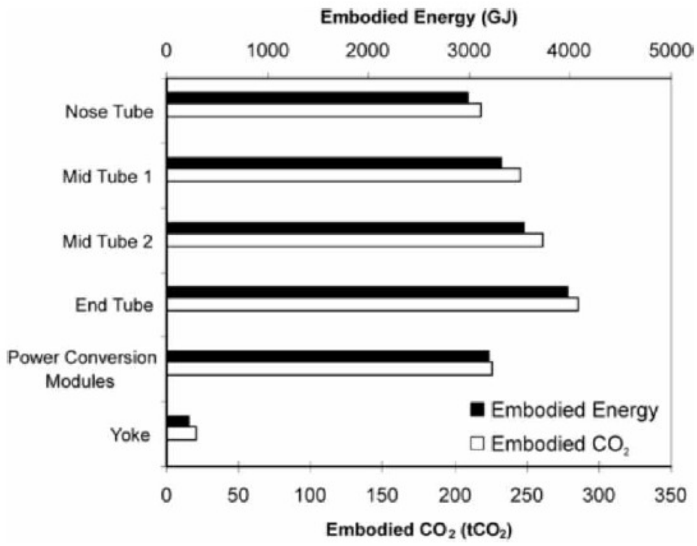


Figure 21 Structural embodied energy and CO_2 of the Pelamis device [3].

2.5 SENSITIVITY ANALYSIS

In LCA it is crucial to understand and quantify the degree of uncertainty in the results. The uncertainty arises in the actual LCI data sources, the volumes of materials and precise detail of processes as well as the assumptions made with regard to allocation and other matters. The simplest approach is to conduct a sensitivity analysis wherein each important variable in turn is adjusted while all others are held constant and provides a rapid method of identifying those to which the outcomes are most susceptible. Other assessments include: scenario analysis which provides a means of understanding how consistent combinations of alternative values can influence the results; and risk (or Monte Carlo) analysis in which the probability distributions of individual variables are estimated and combined into an overall probability estimate. Many LCAs for renewable technologies show a sensitivity analysis as a minimum, e.g., Vestas includes a large sensitivity analysis in their study [5] coving a wide range of factors. The most important factors to test are described in the following points.

2.5.1 Energy Production and lifetime

Figure 22 shows that the influence of annual electricity production on global warming (or CO_2 intensity) is very significant for the Vestas wind turbine [5]. The lifetime of the power plant would have a similar effect as the yearly production. In this case, the calculation presumes that all factors except electric power generation are static, i.e. that there has been no consideration of the infrastructure changes required to exploit better wind conditions at a different location.

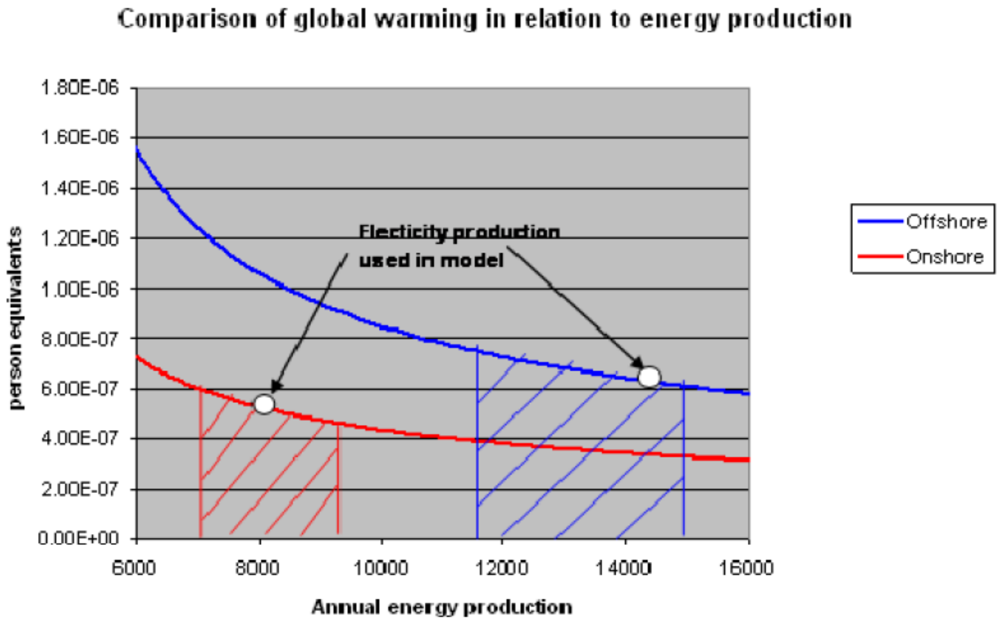


Figure 22 Comparison of global warming impact of V90 wind turbine in relation to energy production onshore and offshore [5].

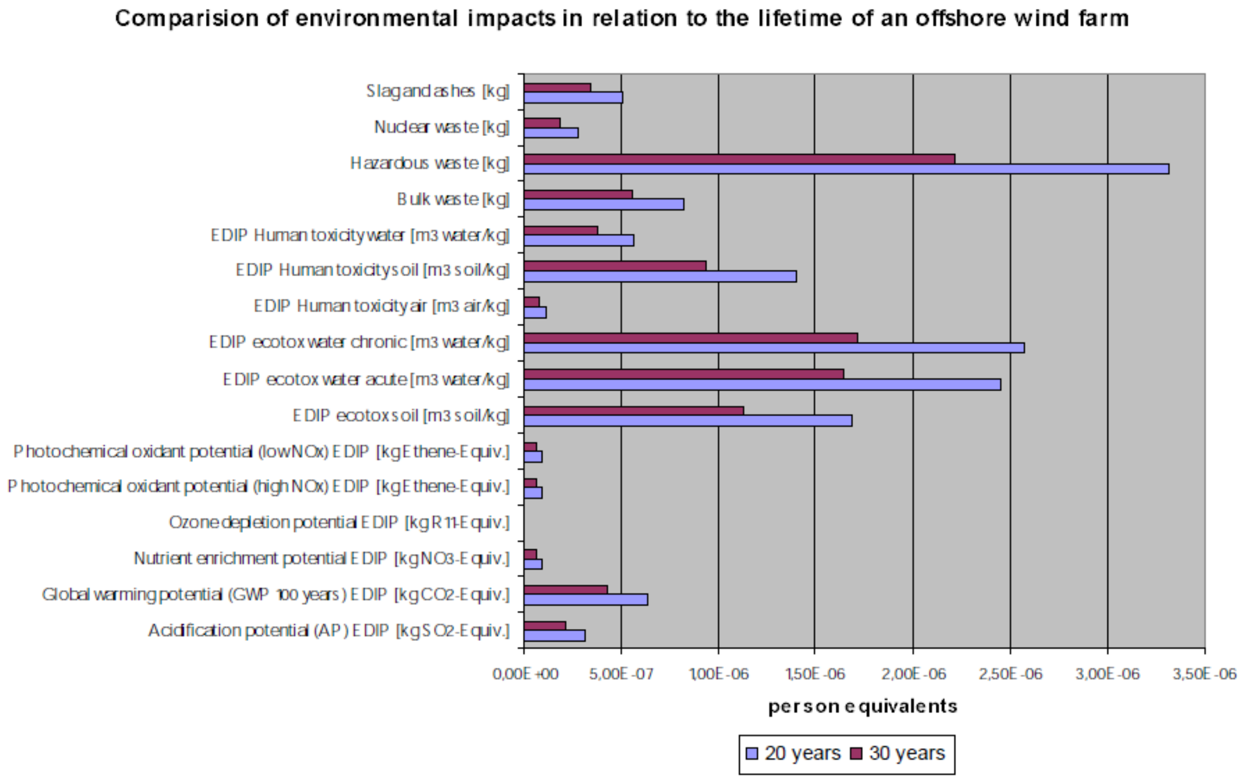


Figure 23 Wind turbine life time influence on environmental effects [5].

2.5.2 Location

Other than through different levels of power generation, the location of onshore wind farms does not appear to have a large effect on the environmental impacts. Offshore and of direct relevance to marine energy technologies, the effect of the cable length is more substantial for installations with a smaller installed capacity. Vestas [5] note a significant impact on water eco toxicity when doubling the distance of the offshore cable.

2.5.3 Materials choice and Recycling

Figure 9 showed the great influence of the recycling rate on all the environmental impacts. Recycling treatment together with energy production and lifetime are the most relevant factors when trying to reduce the environmental impact of products. It can be observed that increasing the recycling rate from 90 to 100% can decrease some environmental impacts by 50% or more. In the same vein, it is important to evaluate the effect of using alternative materials in the manufacturing of devices. Figure 24 shows a large decrease of global warming effect when changing from steel to concrete in the structure of Pelamis [3]. This may also be correlated with a decrease on the costs of the device.

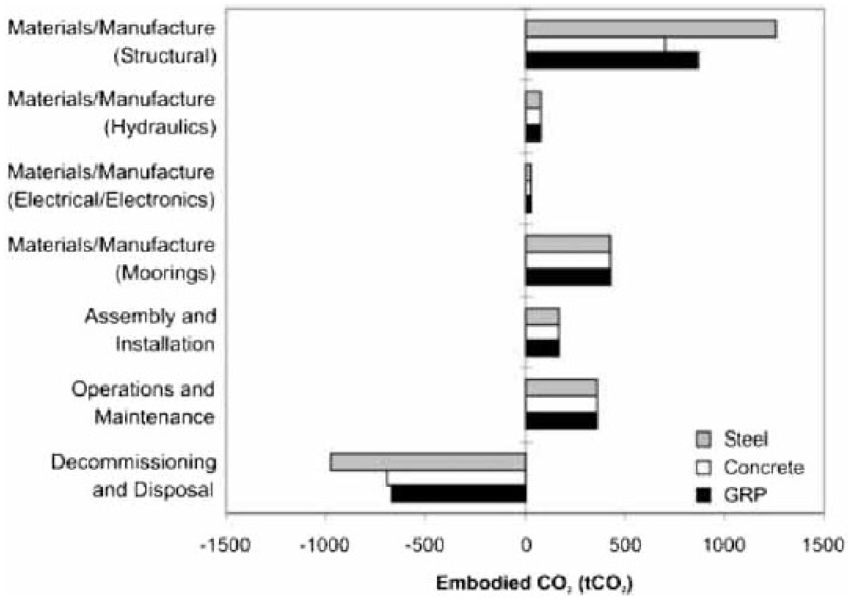


Figure 24 Comparison of embodied CO_2 with alternative materials for Pelamis [3].

2.5.4 Other factors

Many other factors can have an influence on specific environmental impacts of marine energy devices. The location has been studied before only in terms of cable length, but it may have local impacts as well. Also the location of the manufacturing may have impacts on the results through, for example, the CO_2 intensity of the energy mix.

3 LCA DATABASES AND TOOLS

Curran et al. [23] identify a range of public, proprietary, and restricted- access LCI databases. It describes activities that aim to develop publicly-available databases in Africa, the APEC region and Asia, Europe, and the Americas (Canada, USA and Latin America). Because of their close association with the distribution of LCI data, LCA software programs that contain inventory data are also included in this effort. The report also lists institutions or organisations that provide LCI data in a less formal way, as this is important to get a feel for the global spread of LCI data. Also with the aim of facilitating access to global LCI data resources, the report provides contact details and information on regional LCA networks and societies. The focus of the report is on LCI databases and LCI data providers. It therefore does not list general environmental or process data sources (i.e. data must be in the form of life cycle inventories), nor does it list institutions working solely with LCA methodology development. Table 4 shows several available national LCI databases. Curran et al. [23] also present databases from industry organisations such as the European Copper Institute (ECI) or the International Iron and Steel Institute (IISI). There are also other sources from academia and research institute. Table 5 presents information on software available for performing LCA.

Table 4 Available national LCI databases [23].

Name	*Contact*	*Email*	*Website*	*Avail-ability*	*Language*	*Data focus (if any)*	*Geographic coverage*	*Number of datasets*
Australian Life Cycle Inventory Data Project	Tim Grant	tim.grant@rmit.edu.au	http://www.cfd.rmit.edu.au/programs/life_cycle_assessment/life_cycle_inventory	Free	English		Australia	>100
BUWAL 250			http://www.umwelt-schweiz.ch/buwal/eng/	Fee or included with SimaPro	German, English, French	Packaging materials	Switzerland	
Canadian Raw Materials Database	Murray Haight	mehaight@fes.uwaterloo.ca	http://crmd.uwaterloo.ca/	Free	English, French	Raw materials	Canada	>10
DuboCalc	Joris Broers	j.w.broers@dww.rws.minvenw.nl	http://www.rws.nl/rws/bwd/home/www/cgi-bin/index.cgi?site=1&doc=1785	Upon request	top level in Dutch/underlying LCA data in English	Construction materials	Netherlands	>100
Dutch Input Output	Mark Goedkoop	goedkoop@pre.nl	www.pre.nl	Licence fee	English	Input-output	Netherlands	>100
ecoinvent	Rolf Frischknecht	frischknecht@ecoinvent.ch	www.ecoinvent.ch	Licence fee	English, Japanese, German		Global/ Europe/ Switzerland	>1000
Eco-Quantum					Dutch			
EDIP	Niels Frees	nf@ipu.dk	www.lca-center.dk	Licence fee	Danish, English, German		Denmark	>100
Franklin US LCI	Mark Goedkoop	goedkoop@pre.nl	www.pre.nl	Available with SimaPro	English		U.S.A	>10
German Network on Life Cycle Inventory Data	Christian Bauer	info@netzwerklebenszyklusdaten.de	www.lci-network.de	On-going	German, English		Germany	
ITRI Database			http://www.itri.org.tw		Taiwanese, English			
IVAM LCA Data	Harry van Ewijk	hvewijk@ivam.uva.nl	www.ivam.uva.nl	Licence fee	Chinese, English	Construction, food, waste, etc.	Netherlands	>1000
Japan National LCA Project	Nakano Katsuyuki	nakano@jemai.or.jp	http://www.jemai.or.jp/lcaforum/index.cfm (in Japanese) http://www.jemai.or.jp/english/lca/project.cfm	Fee	Japanese		Japan	>600
Korean LCI	Tak Hur	takhur@konkuk.ac.kr	http://www.kncpc.re.kr	On-going				
LCA Food	Per Nielsen	pn@ipl.dtu.dk	www.lcafood.dk	Free	English	Food products	Denmark	
SPINE@CPM	Sandra Häggström	sandra.haggstrom@imi.chalmers.se	www.globalspine.com	Fee	English	-	Global	>100
Swiss Agricultural Life Cycle Assessment Database (SALCA)	Thomas Nemecek	thomas.nemecek@fal.admin.ch	www.reckenholz.ch/doc/en/forsch/control/bilanz/bilanz.html	Free with contact	German	Agriculture	Switzerland	>100
Thailand LCI Database Project	T. (Rut) Mungcharoen	thumrong@mtec.or.th	www.mtec.or.th		Thai, English			
US LCI Database Project	Michael Deru	michael_deru@nrel.gov	www.nrel.gov/lci	Free with contact	English		US	73

Table 5. Available LCA Software [23].

Name	*Contact*	*Email*	*Website*	*Availability*	*Language*	*Data focus (if any)*	*Geographic coverage*	*Number of datasets**
BEES 3.0	Barbara Lippiatt	blippiatt@nist.gov	http://www.bfrl.nist.gov/oae/software/bees.html	Free with contact	English	Building materials and products	USA	200
Boustead Model 5.0			http://www.boustead-consulting.co.uk/products.htm	Licence fee	English		Global	
CMLCA 4.2	Reinout Heijungs	heijungs@cml.leidenuniv.nl	http://www.leidenuniv.nl/interfac/cml/ssp/software/cmlca/index.html	Licence fee only for commercial use	English		Europe	
eiolca.net	H. Scott Matthews	hsm@cmu.edu	www.eiolca.net	Free	English	Input-Output	USA	>100
EMIS	Fredy Dinkel	f.dinkel@carbotech.ch	www.carbotech.ch	Licence fee	English, German		Global	>1000
Environ-mental Impact Estimator	Wayne B. Trusty	wayne.trusty@athenasmi.ca	http://www.athenasmi.ca/tools/	Licence fee	English	Building materials and products	Canada, USA	>10
GaBi	Daniel Coen	d.coen@pe-europe.com	http://www.gabi-software.com/	Licence fee	English, German, Japanese		Global	>1500
GEMIS			http://www.oeko.de/service/gemis/en/index.htm		English, German		Europe	
GREET 1.7	Michael Wang	mqwang@anl.gov	http://www.transportation.anl.gov/software/GREET/index.html	Free	English	Transportation sector, energy sector	USA	>20
IDEMAT 2005		idemat@io.tudelft.nl	http://www.io.tudelft.nl/research/dfs/idemat/index.htm	Licence fee	English	Engineering	Netherlands	>100
KCL-ECO 4.0	Catharina Hohenthal-Joutsimo	Catharina.hohenthal-joutsimo@kcl.fi	http://www.kcl.fi/eco	Licence fee	English		Global	
LCAiT	Lisa Hallberg	lisa.hallberg@cit.chalmers.se	http://www.lcait.com/	Licence fee	English			
MIET			http://www.leidenuniv.nl/cml/ssp/software/miet/index.html					
AIST-LCA (JEMAI-LCA)	Kiyotaka Tahara	k.tahara@aist.go.jp	http://unit.aist.go.jp/lca-center/english/theme.html	Licence fee to JEMAI	Japanese		Japan	>500
Regis	Martin Kilga	martin.kilga@sinum.com	www.sinum.com	Licence fee	English, German, Japanese		Global	
Simapro	Mark Goedkoop	goedkoop@pre.nl	www.pre.nl	Licence fee	English, Japanese		Global	>1000*
TEAM			http://www.ecobalance.com/uk_team.php				Global	
Umberto	Jan Hedemann	j.hedemann@ifu.com	www.umberto.de	Licence fee	English, German, Japanese		Europe	*

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