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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Draft protocol on Life Cycle Analysis approach

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Alex Raventós, Teresa Simas, André Moura
Wave Energy Centre
Gareth Harrison
The University of Edinburgh
Timothy Stallard
University of Manchester

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Summary

This reports aims to review and give advice on the assumptions in order to reach realistic and comparable results within the marine 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, in each of these phases, it shows data and examples from LCA performed on marine technologies or in other renewable technologies (especially wind). Finally this deliverable is a draft of a future deliverable (D6.4.2 Protocol on how to proceed in Life Cycle Analysis of ocean renewable), which aims to be a reference model for the use of LCA analysis for marine technologies.

CONTENTS

1 INTRODUCTION TO LIFE CYCLE ANALYSIS

Global warming due to emissions of green house gases in human activity is probably the most challenging environmental issue up to date. Fortunately science and technology development today can meet the needs of humanity through a transition to a low carbon economy. However, the pace at which this transition will be done will be critical to minimize the effects on the environment. In this context, it is crucial to evaluate the environmental performance of products and processes in order to minimize its Green House Gases (GHG) emissions as well as hazardous wastes and other emissions that may provoke significant impacts on the environment in order to select the best options.

Energy use is the main contributor to the greenhouse effect mainly due to combustion of fossil fuels in transports, 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 the 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 can be allocated to them. In this sense, that can evaluate these impacts. The term life cycle indicates that the analysis will cover all stages in 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 assessing the environmental impacts on every life stage like the CO_2 emissions in the manufacturing of a wind turbine or a wave energy converter. In fact it permits evaluate a large number of impacts.

Life Cycle Analysis or Assessment (LCA) is a methodical analysis which follows an international standard (ISO 14040) but requires time and experience, especially in the definition of the different assumptions. Previous results from the few LCA studies that have been performed up to date on wave and tidal devices show good environmental performance compared to conventional power plants or other renewables as solar PV or biomass. The technologies that have best results in global warming up to date are nuclear, large hydro and wind, followed by wave and tidal energy ([2], [3]).

The early stage of development of marine technologies do not require extensive LCA analysis in order to assess the environmental impacts as it can be a time consuming process, and previous results show that they have a good performance. Indeed, until recently, very few studies were performed for more mature technologies as wind or solar PV. However, LCA analysis represents a very 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 companies like VESTAS to perform this analysis over their products ([4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms.

[5], [4]). In fact this methodology can be very useful in order to reduce costs at the same time as minimizing the environmental impacts. That is why an increasing number of companies use LCA to evaluate their products, processes and materials.

This reports aims to review and give advice on the assumptions in order to reach realistic and comparable results within the marine 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, in each of these phases, it shows data and examples from LCA performed on marine technologies or in other renewable technologies (especially wind). Finally this deliverable is a draft of a future deliverable (D6.4.2 Protocol on how to proceed in Life Cycle Analysis of ocean renewable) which aims to be a reference model for the use of LCA analysis for marine technologies.

1.1 ISO 14040 AND 14044 STANDARDS

LCA represents a new tool to estimate the cumulative environmental impacts resulting from the whole product life cycle, often including impacts ignored in the 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.

The LCA process is standardized by the International Organization for Standardization. A first standardization led to the development of International Standards Organization (ISO) 14000 series:

- ISO 14040: 1997 Environmental management - Life cycle assessment - Principles and framework
- ISO 14041: 1998 Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis
- ISO 1402: 2000 Environmental management - Life cycle assessment - Life cycle impact assessment
- ISO 1403: 2000 Environmental management - Life cycle assessment - Life cycle interpretation

Recently revised by the two ISO:

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

All the ISO standards are not available for consultation. They are sold at the site www.iso.org. 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" (ISO 14040:1997)

According to ISO, LCA is a procedure constituted by four different phases (Figure 1):

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 and inventory of inputs and outputs per functional unit.

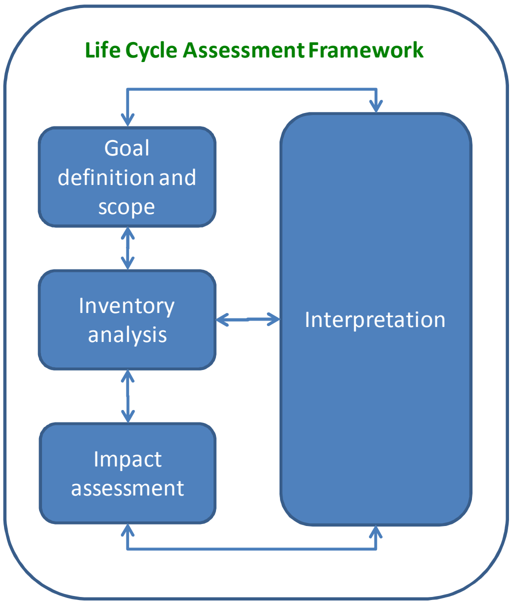


Figure 1 Phases of a LCA (adapted from **Error! Reference source not found.**]).

3. Impact Assessment – Assess the potential human and ecological effects of the inventory items identified in the inventory analysis. Contribution to impact categories such as global warming and acidification are evaluated. The Impact Assessment phase consists of three steps, performed by LCA software tools which, according to the ISO standard, are voluntary steps:
   a. Calculation of impact potentials (based on the LCI results)
   b. Normalization, that provides a basis for comparing different types of environmental impact categories (all impacts are changed in the same unit)
   c. Weighting, that implies assigning a weighting factor to each impact category depending on the relative importance assigned.
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.

2 REVIEW OF LCA FOR MARINE ENERGY TECHNOLOGIES

Examples of LCA of renewable energy technologies can be found in [5], [6], [7] and [8]. LCAs for wave energy devices have also been published for Wave Dragon [9], Seagen [10] and Pelamis [3].

In this section, most LCA studies performed on marine technologies up to date are reviewed following the LCA scheme. The aim of this report is to present the methodology and discuss the importance of the assumptions that are made when performing an LCA with examples of case studies.

Baumann and Tillman [11] introductory book on LCA is recommended as a reference to start with LCA methodology. This report follows the structure of this book as well as the extensive LCA analysis performed by VESTAS together with ELSAM Engineering of turbines V80 and V90 both onshore and offshore ([4], [5]) reviewed by the Danish company FORCE Technology.

2.1 Goal and Scope

2.1.1 Goal definition

The goals of Elsam Engineering [4] LCA evaluation of Vestas turbine V80 are: 1) to use life cycle assessments to environmental improvement strategies in connection with product development, and partly 2) to use LCA-data for preparation of an environmental declaration of contents for electricity produced on turbines. Vestas updated report [5] on turbine V90 includes also a third purpose: to improve the existing LCA model for Vestas wind turbines.

These studies permitted Vestas to know which are 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 recyclability of raw materials, etc.).

Due to the early stage of development of wave and tidal converters, studies were developed to obtain a first estimation of the carbon and energy payback period for these technologies ([12], [13]). Studies that included the contribution of processes and stages on carbon/energy intensity were carried out for Pelamis [2] and Seagen [3] while, for Wave Dragon, a wider range of impacts were evaluated ([9], [14]).

Some other applications for performing LCA for marine technologies may be strategic planning and marketing when comparing with other technologies or competitors. 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 LCA on different renewable energies compare different technologies ([15], [16]), or the influence of external factors in the overall performance of the products (e.g. location of the power plant [17]).

2.1.1.1 Target Group

The target group to whom the LCA is directed is also crucial when defining the goal of the study. Elsam study [4] refers to two target groups: 1) The Danish turbine industry, including employees in VWS A/S' departments of environment and improvement of an integration of environment in the product improvement; 2) The interested public including the Danish Energy Authority shall be able to use the overall results as part of an assessment of the turbine's environmental characteristics.

Vestas posterior LCA target groups where the following four: 1) Customers of Vestas; 2) Vestas Wind Systems A/S; 3) Investors of 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.

Force Technology commented in the report review the importance of offering suitable information for the target group. Thus, the group should be well defined.

2.1.2 Scope of the study

The scope of the study refers to all the choices to make when performing an LCA. These include the choice of which options to model, functional unit, choice of impact categories and method of impact assessment, system boundaries and principles for allocation, and data quality requirements. The following points to define in a generic LCA are [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 with the description of the following topics (following Vestas LCA studies).

2.1.3 Functional Unit

The functional unit for electricity production plants is always defined as 1kWh produced on 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 comparing results between different technologies or within the same technology with different power plates.

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 (ISO 14040 1997). 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 (e.g. CO_2 emissions and/or energy use ([3], [10], [15], [17], [18] and [19]). Such study is called life cycle inventory analysis instead of life cycle assessment.

ISO 14042 (2000) 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 it will be discussed later (e.g. EDIP, Ecoindicator-99, etc.), each one of them with slightly different impact categories. Main differences are found on the weighting methodologies.

Table 1 shows the impacts assessed in some of the LCA reviewed for this report. It can be observed that most of the studies performed in marine energies and wind are focused on CO_2 emissions and energy use during its lifetime. The climate change issue represents an important challenge and must be addressed; however 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]). It has only been found one paper [9] on wave studying most of the impacts; however this study is very generic and performs 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 may point out that results on most of the impacts in emissions may be negligible when compared to conventional power plants or other renewables as biomass or solar PV (e.g. eutrophication, acidification, etc.) as shown in [4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms.

[5], [4] and [6]. 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]. Land use has not been addressed yet and it will probably be one of the weakest points compared to conventional plants.

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] [9] [12]	[2]	[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4][6][17][18]	[15][19]
Ozone-depletion	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4]	
Acidification	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4] [6]	[15]
Eutrophication	[9]		[4] Elsam Engineering. (2004). Life Cycle	[15]

[1] Most of the studies included do not perform the impact assessment but indicate at the inventory level de CO_2 emissions per KWh.

			Assessment of offshore and onshore sited wind farms. [5][4] [6]	
Photochemical smog	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5] [6]	
Human toxicity	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4]	
Ecotoxicity	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4] [6]	
Abiotic resource depletion			[6]	[15]
Biotic resource Depletion				
Energy Intensity/Payback[2]	[3][9][12]	[2]	[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4] [6][17] [18]	[15][19]
Bulk waste	[9][20][3]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4]	[15]
Slags and ashes	[9]		[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5]	

[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.

Hazardous waste	[9]	[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4]
Radioactive waste	[9]	[4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. [5][4]
Land use		

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.

2.1.5.1 Life cycle stages

All process from raw material extraction (including energy) to end of life and disposal should be included when performing a life cycle analysis. For electricity production technologies the life cycle is normally separated in four stages:

Figure 2 Life Cycle Stage for electricity production plants.

Studies on Pelamis and Seagen use the scheme showed in Figure 2. Elsam and Vestas maintain the same four stages calling the second stage 2 (assembly & installation) as transport and erection, and stage 4 as dismantling and scraping. However other studies may aggregate the life cycle in other stages. As an example, LCA on Wave Dragon included in NEEDs project report [14] 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, deposit, recycling or a combination of them. As it will be commented in the following chapters, the rate of recyclability 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.

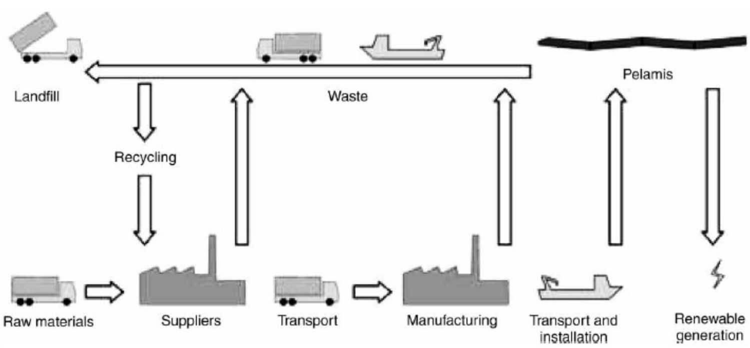


Figure 3 Detailed product life cycle for Pelamis [3].

2.1.5.2 Physical Boundaries

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

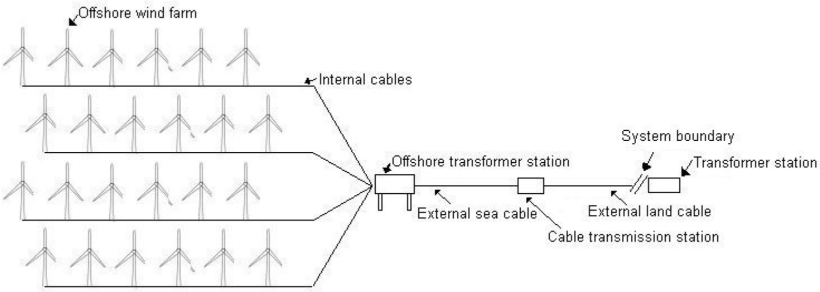


Figure 4 Sketch of offshore wind power plant structure with system boundary for the LCA [5].

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 [14] included a farm of 23 devices of 7MW each, the internal cables, transformer station, marine transmission cable and a cable transmission station. Each of these steps included materials, manufacturing, transport, erection, operation and disposal, but it did not include the external land cable to the national grid transformer. Pelamis and Seagen studies encompassed only one device the moorings and umbilical sub-sea transmission cable (see Figure 5Figure 1) but all downstream elements of the electricity transmission system are outside the scope of the LCA. This fact is probably due to the fact that the scope was to perform an analysis for one single device (up to date no commercial farms are still active) but further studies may address a farm analysis to account for all the environmental impacts of installing these devices.

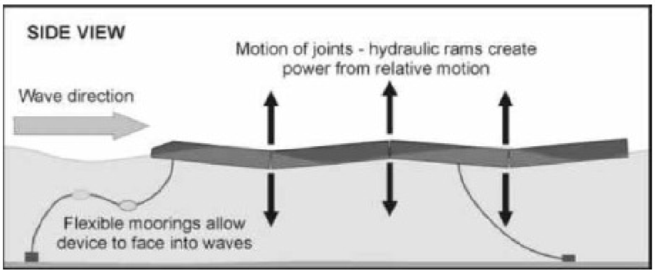


Figure 5 System boundaries for Pelamis LCA [3].

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 inform of the data sources in terms of location and time, 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. 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, 430 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 (no Nuclear power and high share of Coal fired plants in Denmark) while the second is performed by Vestas who claims to use 65% of their electricity from neutral CO_2 sources, which will have a very positive impact on the embodied CO_2 of their products. 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		>430	[12]

2.1.5.4 Lifetime and Production

Results from the LCA are related to the functional unit kWh. Thus the lifetime of power plant and transmission components will greatly affect the results of the environmental analysis as it is further explained in section 2.5. Almost all studies on renewable energy plants assume that the lifetime of plant and 20 years, although in some cases it may exceed this value. Wave Dragon [9] LCA assume a lifetime of 50 year which will reduce the impacts in 2.5 times with respect to other LCA analysis performed on other technologies. Production is normally referred as annual equivalent hours or capacity factor. Production values depend on the type of energy and selected technology, but also on the location of the plant, the year (state of art of technology), lifetime and capacity factor. Literature does not describe assumptions on reduction of 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. Then, the decrease in production should be accounted while performing the LCA or applied an average annual production value. As mentioned in the previous section, it is also very important to inform the date of the data used for the inventory analysis as the development in terms of technology, processes and materials may probably change greatly in time.

2.1.6 Data Quality

Baumann and Tillman [11] states 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 assessing a whole sector as wave energy due to the different technologies and locations of the plants, but may be more rigorous when performing over a specific model or technology to obtain a green certificate.

ISO standard (14041 1998) 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 an external entity with experience performs a critical review of the process [5].

2.1.8 Software and Databases

Several software and databases are freely or available with the payment of a fee. Actually, databases with large number of datasheets are only paying and the more complete at European level is Ecoinvent. EDIP has also been used but it accounts only for Denmark. Most used commercial software tools are Gabi and SimaPro. A resume of database and software available is included in section 3.

2.2 INVENTORY ANALYSIS

2.2.1 Construction of the Flow Chart

The construction and implementation of the 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, and they should be written in order to inform of them. An example of flow chart is shown in Figure 6.

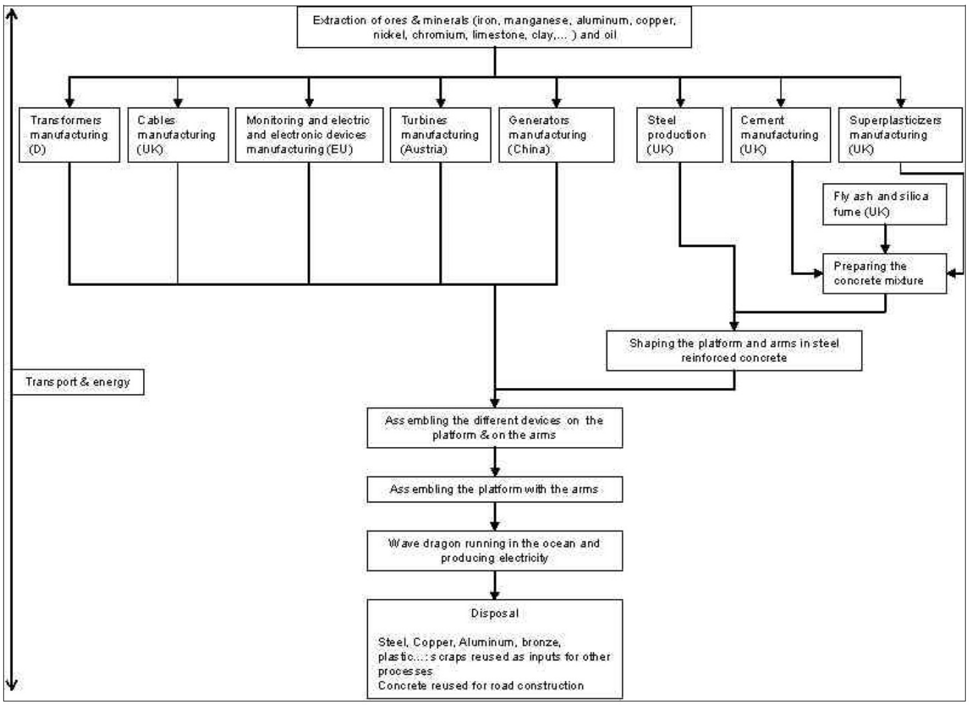


Figure 6 Flow chart of the life cycle of Wave Dragon [9].

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 it will be obtained several outputs, 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).

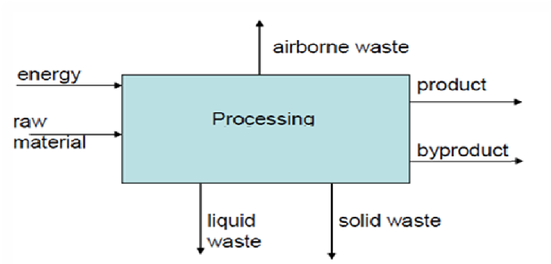


Figure 7 Processes included in LCA.

2.2.2 Data Collection

As stated before, when performing a LCA, the first intention should be to collect the most accurate data of inputs (raw materials including energy) used during the whole life cycle should be introduced in the model. 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 LCA on renewable energies 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 the solid wastes of the processing.

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, the Internet and other LCA studies. In some cases, it is necessary to make assumptions about the materials which should be described on the study [4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms.

[5].

2.2.2.2 Planning for data collection

Before starting to look for data it is important to think in some tips. First it is important to think on which activities are the most important so more effort and detail should be addressed to those. Vestas [4] concluded that concerning the turbines, the most significant environmental impacts will most typically arise during manufacturing of the turbines and final disposal of the turbines. On the other hand, the operational stage does not contribute significantly to environmental impacts. Therefore, data collection has been focused on procuring as precise data as possible for the production and disposal stages. Vestas also differences into first level materials (i.e. materials used on Vestas factories, e.g. Prepreg for blades and steel for towers) and second level processes (i.e. resources, materials and consumables used by sub-suppliers, e.g. energy used in the manufacture of steel profiles and content of substances in Prepreg) trying to cover 95% of the first and prioritising the important information for the second. LCA performed on Pelamis [3] states that the primary focus of this 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 (so need specific data) and which activities average data is preferred. Finally, before approaching suppliers it is important to be prepared regarding how to approach (which department, questionnaire or checklist), technical information, confidentiality issues, etc. [11].

2.2.2.3 Validation of data

ISO 14041 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's guide to perform an LCA, 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 one of the products (the product is kWh in energy generation) or input for waste treatment processes. In theory is 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 as related to the flow representing the functional unit. This is a simple operation, since step 2 has given the size of the linking lows 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 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 as shown in the figure so the impact assessment methods permit to organise and understand the data as it will be shown in section 2.3.

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

Table 3 (*continued*)

Material	Amount/power plant	Unit	Amount/MJ	Unit
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" **[6]**.

2.2.3.1 Allocation

As ocean power devices (e.g. turbines) only produce and e.g. 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 [5].

2.2.3.2 Accounting for recyclability rate

Most marine renewable technologies are usually defined by large metallic structures and thus the high rate of recyclability has a huge importance on the overall results of the LCA. When performing a LCA recycling can be considered as saves or credits part of the energy and carbon needed for the manufacturing of the materials. Vestas, first world's turbine manufacturer, considers a recyclability rate of iron in their turbines of 90% in their LCAs [4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms.

[5] [4] and is pushing to achieve 100% of iron recyclability. Due to the positive impact of recyclability they also performed a sensitivity analysis of it in the environmental impact if increasing the rate to 95% and 100% with large improvement (see Figure 9).

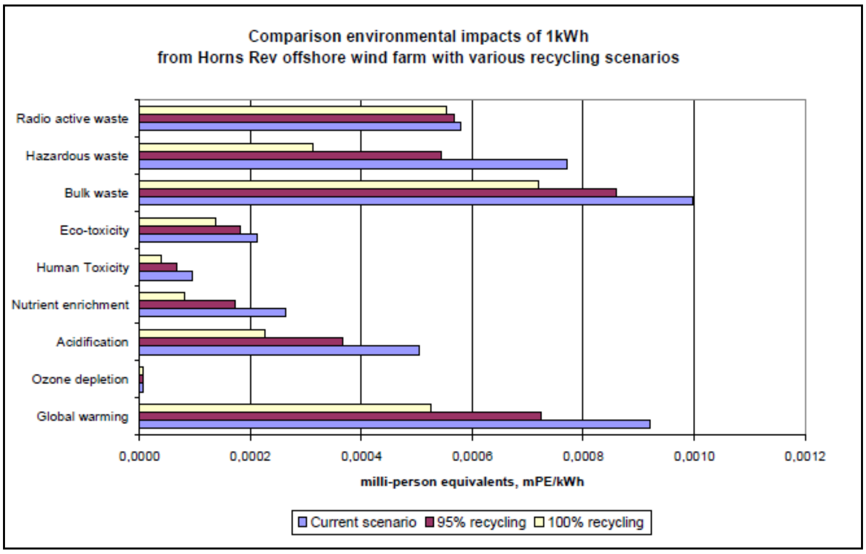


Figure 9 Comparison environmental impacts of 1kWh from Horns Rev offshore wind farm with various recycling scenarios.

In the case of other marine technologies it may be still early to know what will be the rate of recyclability but offshore wind experience may serve as a benchmark for wave and tidal as they share similarities in the structure. In this sense, LCAs on wave [3] and tidal [2] consider the same rate of iron recyclability at 90%.

2.3 IMPACT ASSESSMENT

The phase called *life cycle impact assessment* (LCIA) aims at describing 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 reason for this translation. For many, it is easier to relate to for example acidification consequences than to SO_2. 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. The number of inventory results parameters can range from 50 to 200 or more. 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 , or even down to one weighting across the impact categories (although this has not been used in LCAs on RES).

There are several methods to assess the life cycle impact of a product. The most commonly used in renewable energies in Europe are probably EDIP (for Denmark) ([9], [4] Elsam Engineering. (2004). Life Cycle Assessment of offshore and onshore sited wind farms.

[5] and [4]) and Ecoindicator-99 (European level) [16]. Also other methods as CML (Germany) [6] or EPA are available.

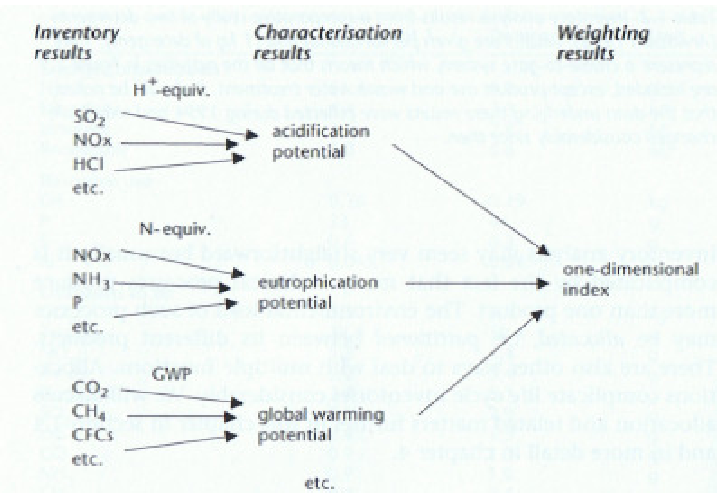


Figure 10 Illustration of the stepwise aggregation of information in LCIA [11].

All these methods converge in 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 (e.g. CO_2, CH_4, CFCs all contribute to GHG effect with different weights each of them). However, the different methods differ in the way they present and weight the different impacts.

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 [21].

Figure 11 presents commonly used life impact categories and Figure 12 presents which are the most significant impacts of energy production forms based on a study [21]. Similarities between wind and wave and tidal technologies can induce that marine technologies will have impacts on sea use, visual impact and/or noise compared to other production options. However, wind energy (and probably marine and tidal) has low impact in resource depletion, greenhouse effect, acidification or eutrophication [21].

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 [21].

Studies performed on marine technologies have been mainly focused on greenhouse effect and corroborate the low impact of these technologies being estimated the carbon intensity on wave around 22,9 gCO_2/kWh [3] and around 15 gCO_2/kWh on tidal [2] compared to around 500 gCO_2/kWh in the actual European mixes (Figure 13). This value is also strongly correlated to the amount of energy used during the whole life cycle and thus contributes to a low resource depletion in terms of energy.

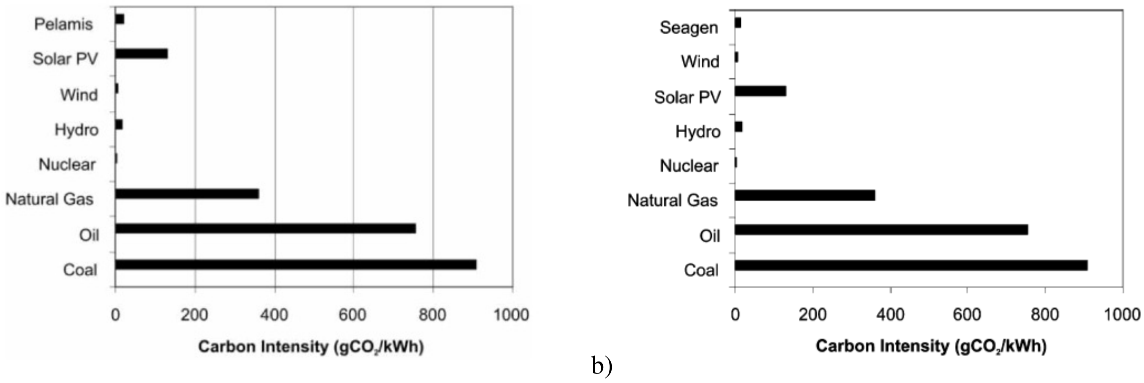
a)


Figure 13 Comparison of carbon intensity from several energy sources.

However, another study performed on several renewable technologies by Pehnt shows that in terms of iron ore requirements, wind energy (as well as solar PV, geothermal and other RES) have more impact on this specific resource than conventional production plants [15]. Tavares and Raventos [20] perform a gross estimation of iron ore requirements for wave energy being estimated around 30% higher than that of wind based on data from Pelamis. 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. Later on, in the sensitivity analysis section, it will be discussed the impact of changing the manufacturing materials.

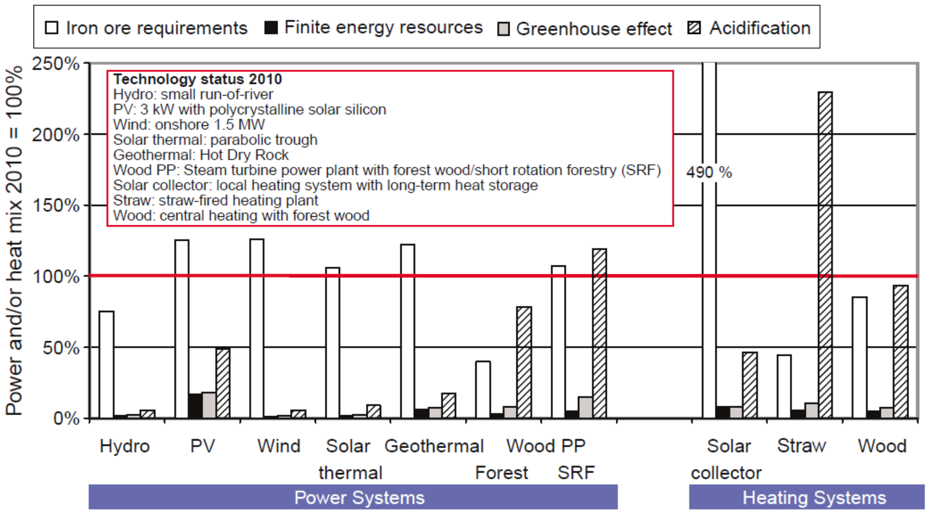


Figure 14 Normalized LCA of selected renewable energy systems for four impact categories [15].

It has only been found a paper studying further impacts on wave energy performed by Wave Dragon and the Technical University of Denmark. Its negative results show that the electricity production from Wave Dragon circumvents both consumption of various fossil fuels and contributions to other environmental impacts like emissions of greenhouse gases, bulk waste and dangerous chemicals [9]. However, the paper does not offer much information on the assumptions adopted for its evaluation and it is supposed a life time of 50 years.

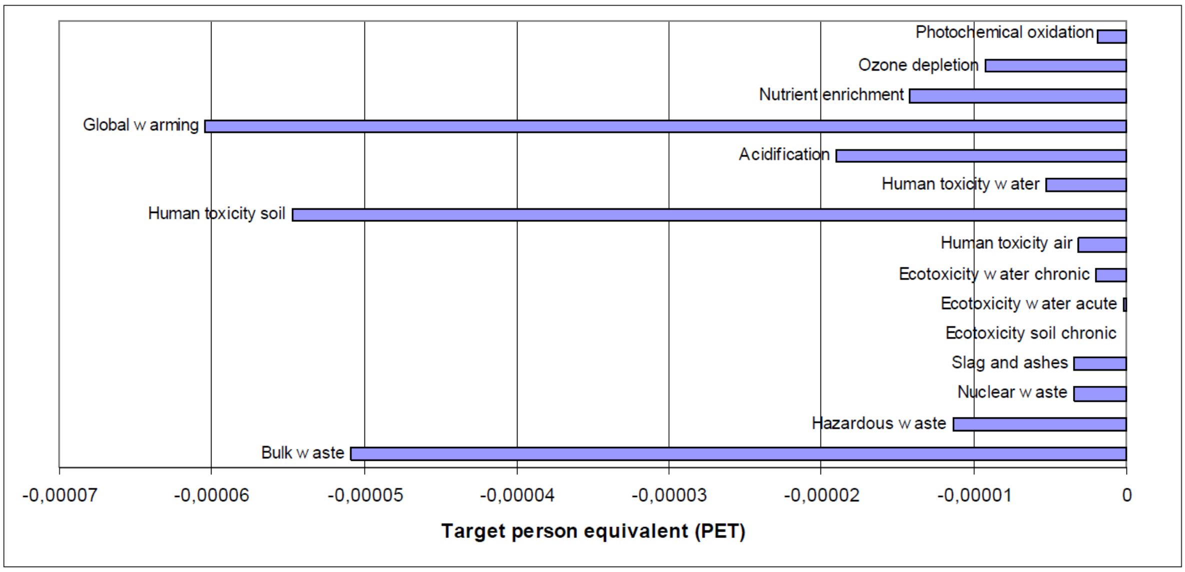


Figure 15 Weighted environmental impact potentials for the whole life cycle [9] (calculated in accordance to the EDIP method).

2.4 Interpretation and Presentation of Results

2.4.1 Units and normalization for results presentation and interpretation

In the previous section several results from previous studies have been shown. It can be observed that there are different approaches to present the results depending on the weighting method use and/or the preference of the user. 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 make up of an average citizen's total impact. This means that the environmental impacts of power from the farms are related to a standard citizen's average contribution to the individual environmental impacts (see Figure 9 and Figure 14).

It may sometimes hard to understand the units of a certain method as EDIP, so it may be a good option to express the results in equivalent physical units (e.g. CO2 equivalents) for a specific impact. Most studies performed on marine and wind devices are focused on greenhouse gas emissions and show results in terms of CO_2 equivalent units per kWh sold and the payback period necessary to produce as much energy as consumed during the whole life or to save the CO_2 emitted. Table 3 summarises results on carbon intensity and payback periods for different marine and other electricity production technologies.

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	22,8	20	13	[3]
Pelamis WEC	25-50		20	[12]
Wave Dragon	13	29		[9]
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			[6]
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]

It can also be very useful to normalize the results by comparing to reference technologies. For example in Pehnt [15] the normalization takes place for electricity generating systems with regard to electricity mix for Germany in 2010. That is, impacts of provision of 1 kWh by means of renewable energy systems are divided by the impacts of the assumed electricity mix as defined in the business-as-usual development (energy carrier split and average power plant efficiency) according to the reference scenario of the German Enquete commission. In other words, a value higher than 100% implies that in the relevant environmental impacts there is an increase in detrimental effect in comparison to the mix; a value below 100% means a reduction. This normalization serves two purposes. On the one hand, environmental advantages and disadvantages of the electricity consumption can be identified easily. On the other hand, different environmental impacts can be represented in one diagram. Tavares and Raventos [20] take the data performed by Penht [15] and introduce average data from studies in wave energy to compare against other technologies.

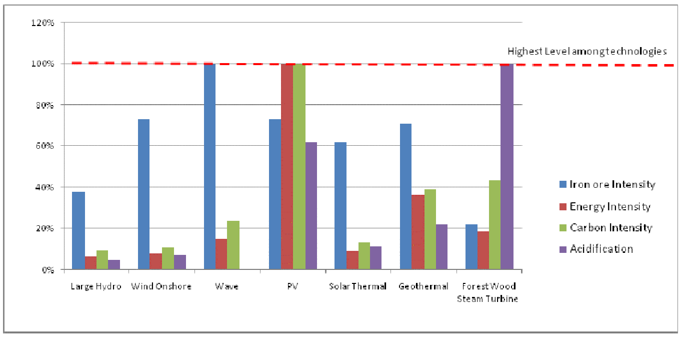


Figure 16 Energy and CO2 intensities compared with the worst performance [20].

Results show that energy and carbon performance for both wind and wave are among the best renewable technologies, together with large hydro and solar thermal. Wind energy intensity represents only 8% of actual 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. However, although not being in the scope of this study, results from Pehnt (2005) shows that wave and wind energy are the most iron intensive technologies among renewable (wave iron intensity has been estimated from Pelamis steel weight and has been added to the results of this study).

Comparing results against the European Mix level, wave and wind carbon and energy intensity 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 intensive than the actual EU Power Mix (being the EU27 mix in 2006: 55% conventional thermal, 30% nuclear, 16% renewables, 1% others).

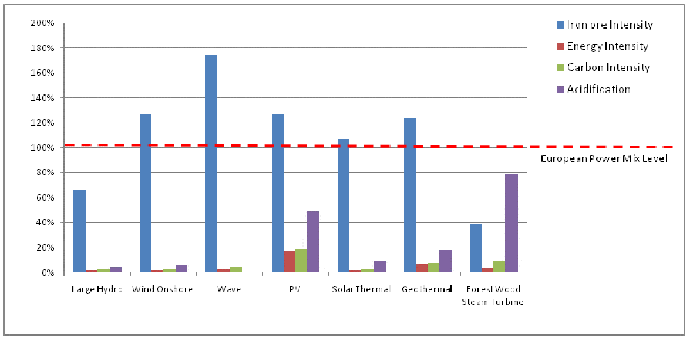


Figure 17 Energy and CO_2 intensities compared with the European Power Mix level [20].

2.4.2 *Allocating the environmental impacts*

LCA analysis permits to break down the impacts per process, material, life stage, etc. This information can be of crucial interest for developers, promoters and operators trying to reduce and optimize the environmental performance of each of the processes of the life cycle.

2.4.2.1 Breaking down the impacts into life stages

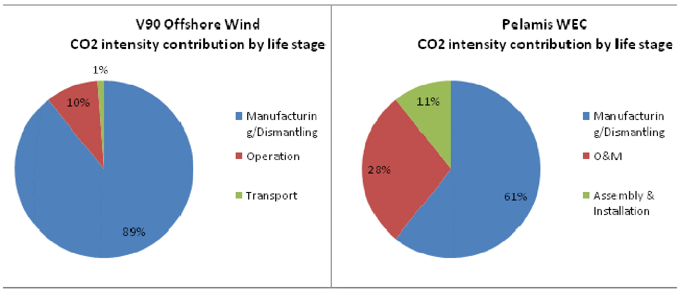


Figure 18 Carbon distribution for offshore wind and wave converter Pelamis ([3], [5], [20]).

Figure 18 presents carbon distribution for offshore wind Vestas V90 and wave converter Pelamis. Manufacturing and dismantling are the main carbon emitter sector of their life cycle, mainly due to manufacturing processes. 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 recycle rate supposed of iron is 90%) which in fact saves or 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 as it is shown further on on the sensititvity analysis section.

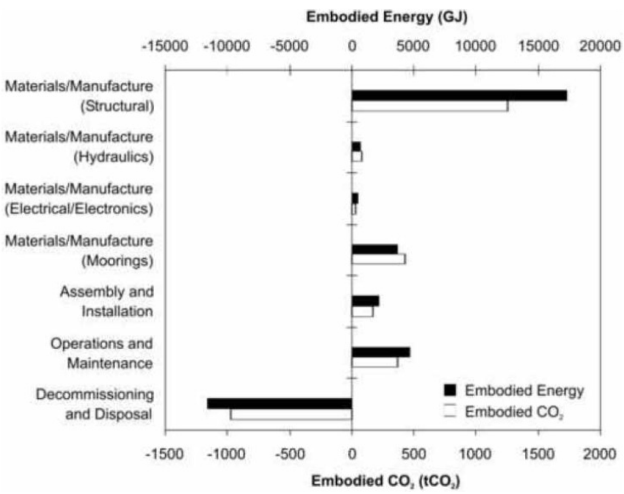


Figure 19 Embodied energy and CO2 by life cycle stage for Pelamis [3].

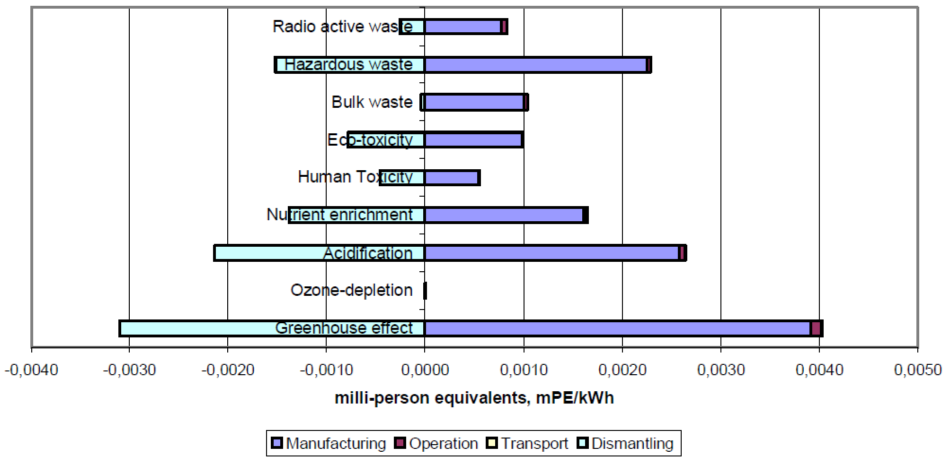


Figure 20 Environmental impacts of 1kWh from Horns Rev offshore wind farm divided into stages [4]

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 down the cost into the components. Figure 21 shows the embodied energy and CO2 on Pelamis P1 device from [3]. This study also gives approximation of the embodied energy and CO_2 of other components as it has been shown in Figure 19, being the moorings also intensive in energy and CO_2 while other components as the hydraulics and electronics have a very small contribution. This type of information can be very useful when defining the depth of the study.

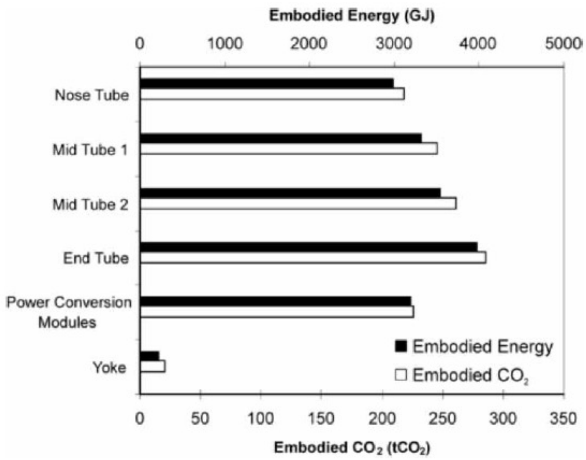


Figure 21 Structural embodied energy and CO_2 on Pelamis P1 device [3].

Results are also broken down into different materials, processes in manufacturing, activities, etc.

2.5 SENSITIVITY ANALYSIS

In LCA analysis is crucial to perform at the end a sensitivity analysis in order to evaluate the influence of the different factors and assumptions on the final results. Vestas includes a large sensitivity analysis in their study [5] in the several factors. The most important factors are described in the following points.

2.5.1 Energy Production and lifetime

Figure 22 shows that the influence of annual electricity production in global warming (or CO_2 intensity) is very significant in study performed by Vestas on their V90 3MW turbines. In the same direction, 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 equal. I.e. no considerations have been made for a better wind location which could require increased material consumption in connection with construction, longer cables, other foundations, etc.

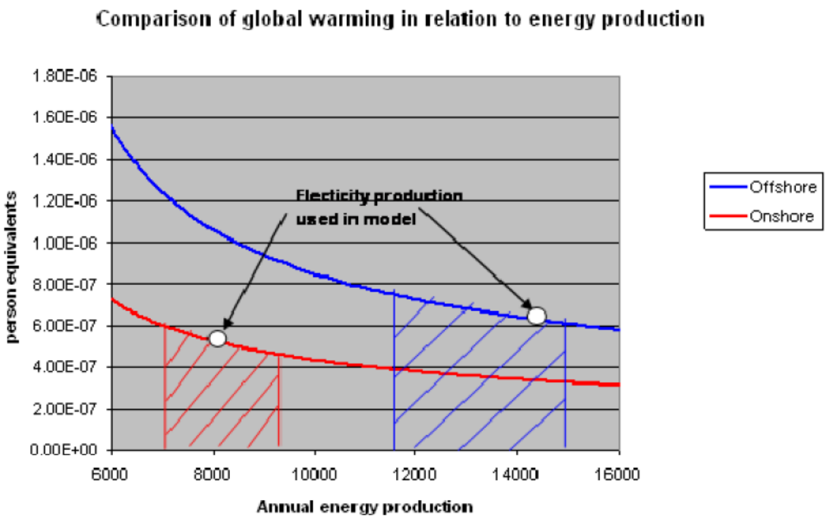


Figure 22 Comparison of global warming impact of V90 wind turbine in relation to energy production onshore and offshore.

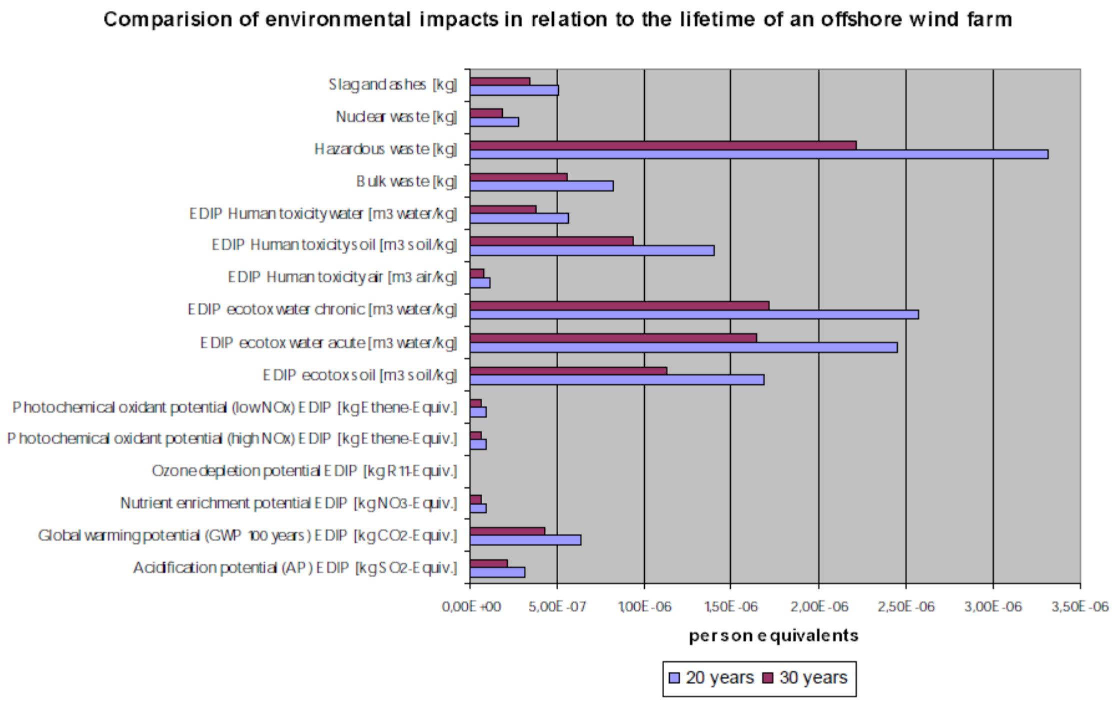


Figure 23 Lifetime influence on environmental effects.

2.5.2 Location

The location of the wind farm for an onshore wind farm (in terms of cable length) does not to have large effect on the environmental impacts. Only in terms of hazardous waste seems to influence significantly the results. However, if accounting for plants with a smaller installed capacity, the locations effects may contribute largely on the environmental impact. Vestas [5] also shows a significant impact when doubling the distance of the offshore cable on the eco toxicity of water.

2.5.3 Materials choice and Recycling

Figure 9 showed the great influence on the recycling rate on all the environmental impacts. Recycling together with energy production (and lifetime) seems to be the most relevant factors when trying to reduce the environmental impact of products. I can be observed that increasing 10% the recyclability rate from 90 to 100% can decrease some environmental impacts 50% or more.

In the same direction, it is important to evaluate the effect of using other 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.

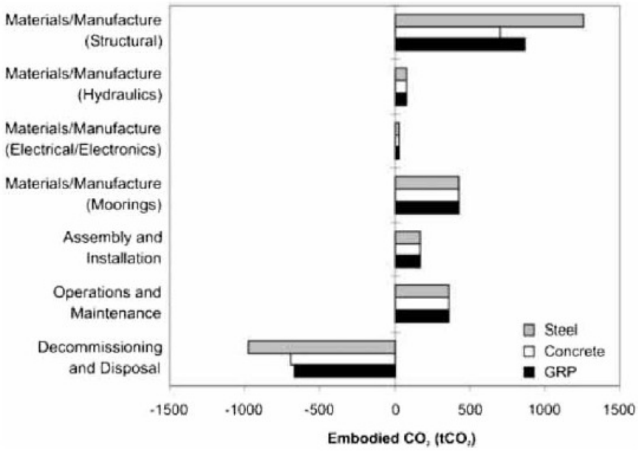


Figure 24 Comparison of embodied CO_2 with alternative materials.

2.5.4 Other factors

Many other factors can have great 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 (e.g. the CO_2 intensity of the energy mix).

3 AVAILABLE DATABASES & TOOLS

Curran et al identify LCI databases including public, as well as proprietary, or restricted- access, databases. It includes descriptions of 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 [22].

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

Figure 25 Available national LCI databases [22].

Curran et al. [22] also present databases from industry organisations as European Copper Institute (ECI) or the International Iron and Steel Institute (IISI). There are also other sources from academia and research institute. Finally Figure 26 presents information on the available software for performing LCA analysis.

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	*

Figure 26 Available LCA Software [22].

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