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# Life Cycle Assessment of Electricity from Wave Power

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## Abstract

The use of ocean wave energy for electricity production has considerable potential, though it has proven to be difficult. A technology utilizing the heaving (up-and-down) motions of the waves was conceived at Uppsala University in the early 2000´s, and is being further developed for commercial use by Seabased Industry AB.

The purpose of this master´s degree project was to increase the knowledge of the environmental performance of Seabased´s wave energy conversion concept and identifying possible areas of improvement. This was done by conducting a life cycle assessment (LCA) of a hypothetical prototype wave power plant. All flows of materials, energy, emissions and waste were calculated for all stages of a wave power plant´s life cycle. The potential environmental impact of these flows was then assessed, using the following impact categories:

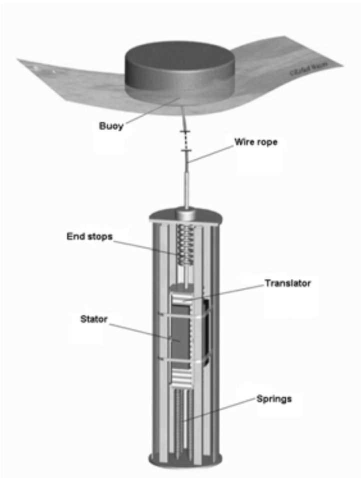
- Emission of greenhouse gases
- Emission of ozone depleting gases
- Emission of acidifying gases
- Emission of gases that contribute to the forming of ground-level ozone
- Emission of substances to water contributing to oxygen depletion (eutrophication)
- Energy use (renewable and non-renewable)
- Water use

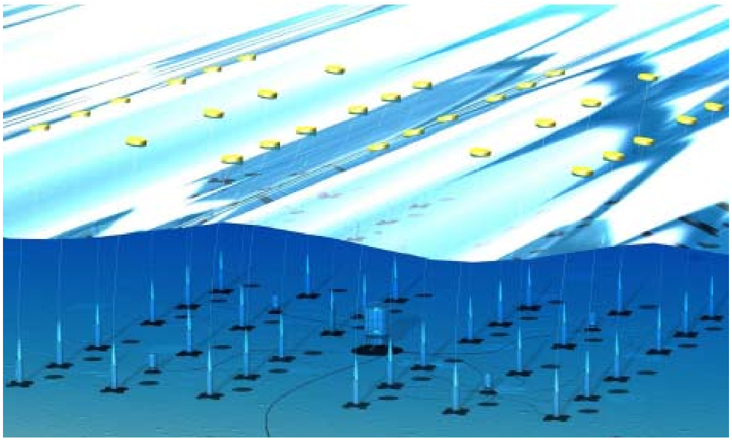
The methodology used was that prescribed by the ISO standard for Environmental Product Declarations (EPD) and further defined by the International EPD Programme.The potential environmental impact was calculated per kWh of wave power electricity delivered to the grid.

The main result of the study is that the potential environmental impact of a wave power plant mainly stems from the manufacturing phase. In particular, the production of steel parts makes a large contribution to the overall results. Future wave power plant designs are expected to be considerably more material efficient, meaning that there are large possibilities to improve the environmental performance of this technology.

# SAMMANFATTNING

Havsvågor innehåller enorma mängder förnybar energi. Många försök har gjorts att utnyttja denna energi, men det har visat sig vara svårt. Ett nytt koncept för att omvandla vågornas vertikala rörelser till elektricitet utvecklades under början av 2000-talet vid Uppsala universitet och utvecklas nu vidare för marknaden av Uppsalaföretaget Seabased Industry AB. Denna teknik bygger på linjära generatorer (d.v.s. generatorer vars rörliga del inte roterar utan rör sig upp och ner) placerade på fundament på havsbotten. Generatorns rörliga del, translatorn, sitter fast med ett vajerrep i en boj som rör sig upp och ner med havsytan. Translatorn är klädd med permanentmagneter och rör sig upp och ner inuti generatorns fasta del, statorn, som i princip är en stor spole. På så sätt alstras elektricitet. Ett stort antal sådana generatorer bildar en vågkraftpark.





**T.V: BOJ OCH LINJÄRGENERATOR. GENERATORN PLACERAS PÅ HAVSBOTTEN OCH DESS RÖRLIGA DEL, TRANSLATORN, RÖR SIG UPP OCH NER MED BOJEN SOM FLYTER PÅ HAVSYTAN. T.H: EN VÅGKRAFTPARK SOM DEN SKULLE KUNNA SE UT I FRAMTIDEN.**

Syftet med detta examensarbete var att öka kunskapen om den miljöpåverkan som orsakas av denna vågkraftsteknik, genom att genomföra en livscykelanalys av en vågkraftpark. Livscykelanalys (LCA) är en kvantitativ metod för att bedöma produkters och tjänsters miljöpåverkan. Förbrukning av resurser och utsläpp av föroreningar beräknas för alla delar av produktens livscykel, från utvinning av råmaterial tills produkten använts färdigt. Miljöpåverkan delas in i olika kategorier och utsläpp av olika föroreningar summeras med hjälp av så kallade karakteriseringsfaktorer. Exempelvis beräknas utsläppen av växthusgaser i koldioxidekvivalenter. Metan beräknas bidra till global uppvärmning 23 gånger så mycket som koldioxid. När man summerar ihop utsläpp av växthusgaser multipliceras därför utsläppen av metan med karakteriseringsfaktorn 23, medan koldioxidutsläpp multipliceras med 1.

Resultaten av en livscykelanalys beror till stor del på vilken metod och vilka systemgränser som används. Därför finns standarder för hur LCA ska genomföras. Miljövarudeklarationer är en typ av miljömärkning som baseras på livscykelanalyser genomförda i enlighet med ISO-standarderna för LCA. Syftet med miljövarudeklarationer är att förenkla jämförelser av miljöprestanda mellan olika produkter som fyller samma funktion. Denna livscykelanalys genomfördes enligt riktlinjerna för miljövarudeklarationer. Miljöpåverkan beräknades per kWh el levererad till elnätet och följande miljöpåverkanskategorier användes:

- Utsläpp av växthusgaser
- Utsläpp av ozonförstörande gaser
- Utsläpp av försurande ämnen
- Utsläpp av ämnen som bidrar till övergödning
- Utsläpp av ämnen som bidrar till bildandet av marknära ozon
- Energiförbrukning
- Vattenförbrukning

Analysen gjordes för två fall. Det första var en vågkraftpark bestående av 1000 generatorer, placerad utanför den svenska västkusten, där vågorna är ganska små. I det andra scenariot placeras en likadan park utanför norska kusten. Vågorna är större utanför Norge och man får alltså ut mer elektricitet. Eftersom vågkraftverken tillverkas i Lysekil blir dock transporterna till utläggningsplatsen betydligt längre i det norska fallet.

Resultaten av analysen visar att konstruktionsfasen orsakar största delen av den miljöpåverkan som orsakas av en vågkraftpark. Det är framför allt tillverkningen av stål till vågkraftverken som förbrukar resurser och orsakar utsläpp. Med andra ord är materialeffektivitet det absolut viktigaste att fokusera på för att minska vågkraftens miljöpåverkan. De vågkraftverk som analyseras i denna studie kan sägas vara prototyper och åtgången av stål beräknas bli betydligt – kanske så mycket som femtio procent - mindre i framtida konstruktioner. Med andra ord finns det stor potential att minska systemets miljöpåverkan. I studien antogs generatorfundamenten bestå av armerad betong, som då utgjorde över åttio procent av vågkraftparkens totala vikt. Betongtillverkning visade sig dock stå för en relativt liten del (som mest tio procent) av miljöpåverkan. Permanentmagneterna, en legering av neodymium, järn och bor, beräknades bidra till lika stor andel av miljöpåverkan, trots att de utgör mindre än en procent av den totala vikten.

Transporter av vågkraftverk till sjöss bidrar till en ganska liten del av miljöpåverkan. Detta innebär att en vågkraftpark utanför Norges kust får mycket bättre miljöprestanda än en park strax utanför Lysekil, trots att transportavståndet är betydligt kortare i det senare fallet. I studien beräknades även vågkraftparkens energiåterbetalningstid, det vill säga den tid det tar för parken att generera den mängd energi som används för att tillverka, underhålla och kassera den. I det norska fallet blev energiåterbetalningstiden cirka tre år, medan den blev nästan tio år i det svenska fallet. Med tanke på att parkens livslängd antas vara tjugo år är detta ett mycket dåligt resultat.

Osäkerheten i resultaten beror dels på osäkerheter i bakgrundsdata (exakt hur mycket svaveldioxid orsakar egentligen produktionen av ett kilo stål?). Osäkerheter i bakgrundsdata uppskattades med hjälp av Monte Carlo-simulering. Denna osäkerhet visade sig vara störst (cirka 50 %) gällande utsläpp av ozonförstörande gaser och minst (cirka 5 %) gällande utsläpp av växthusgaser. Eftersom studien avser hypotetiska vågkraftparker har många antaganden och uppskattningar gjorts, vilket också orsakar osäkerhet i resultaten. Även om man tar hänsyn till denna osäkerhet bör dock de slutsatser som redovisas ovan kunna dras.

# CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# 1 Introduction

## 1.1 Background

### *1.1.1 Wave Energy Conversion – the Uppsala Concept*

The oceans of the world represent an enormous, renewable source of energy which so far remains virtually unexploited. A growing energy demand combined with pressing environmental concerns makes wave power interesting from an economical as well as an environmental point of view. However, wave energy conversion has proven to be difficult. In spite of decades of research and thousands of patents there is still no consensus on the best way to harness the energy of ocean waves. Waves are an irregular source of energy and the variations in power flow can be very large – when a storm hits, the power flow of the waves can be fifty times larger than the average (1). Further, the corrosive environment and difficulties with accessibility for maintenance out at sea present problems that must be solved. Designing a device that is economically viable as well as robust enough to handle the rough conditions of the ocean is truly a challenge.

The wave energy conversion research project at Uppsala University is based on a system utilizing the heaving (up-and-down) movement of the waves. A buoy floating on the ocean surface is connected by a wire rope to a linear generator on the ocean floor. The generator consists of a moving part (translator), which is clad with permanent magnets, and a stationary part (stator) with three-phase cable windings. The translator moves up and down, following the motions of the buoy, generating a voltage in the cable windings of the stator. The principle is the same as when a magnet is moved back and forth through a coil, with the translator representing the magnet and the stator representing the coil. A wave power plant is envisioned to consist of a large number (up to several thousands) of generators placed in arrays on the seafloor. Figure 1 is a schematic illustration of a wave energy converter and figure 2 shows a vision of what a wave power plant of this type might look like in the future.

The benefits of this concept are that the electrical components of the plant are placed on the bottom of the sea, sheltered from the large forces acting on the sea surface. Using linear generators also means that no hydraulic or mechanic system is needed to convert the wave motions into the fast, rotating movement of a conventional generator. This means a less complex and more robust construction. Another benefit is the use of many small units instead of one large construction. This decreases the vulnerability of the plant – a few generators can break without significantly affecting the total electricity production of the plant. The technology is further described in chapter 4.

The described wave energy conversion system is currently being further developed for commercial use by Seabased Industry AB in Uppsala. The technology is at an early stage of development and the wave energy converters so far constructed by the company are more or less prototypes. The hope is that wave power in the future will be both economically viable and environmentally sound.

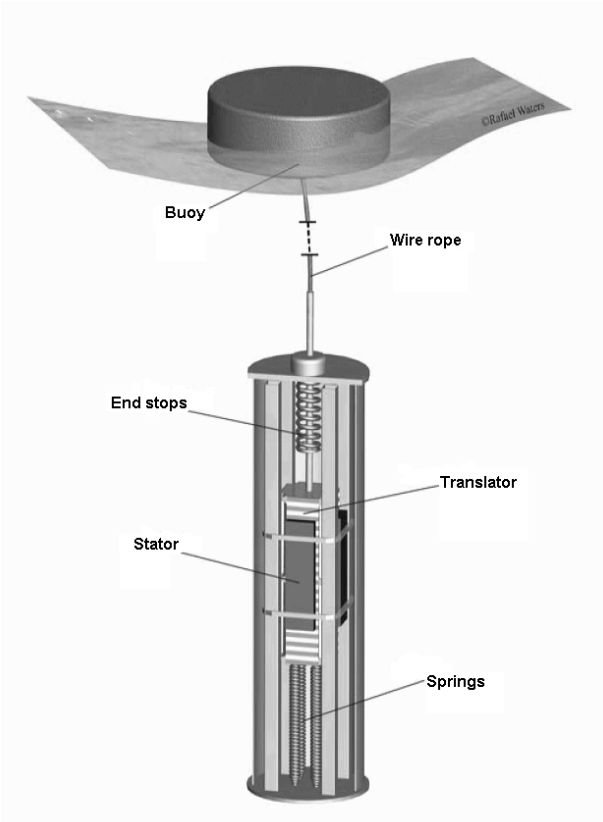



**FIGURE 1: THE STRUCTURE OF A WAVE ENERGY CONVERTER (WEC). THE TYPE OF WEC USED IN THE PRESENT STUDY DIFFERS FROM THIS SCHEMATIC BY NOT USING SPRINGS TO PULL THE PISTON DOWN. INSTEAD, THE TRANSLATOR WILL MOVE DOWNWARDS IN THE WAVE TROUGHS BY ITS OWN WEIGHT. ©RAFAEL WATERS**

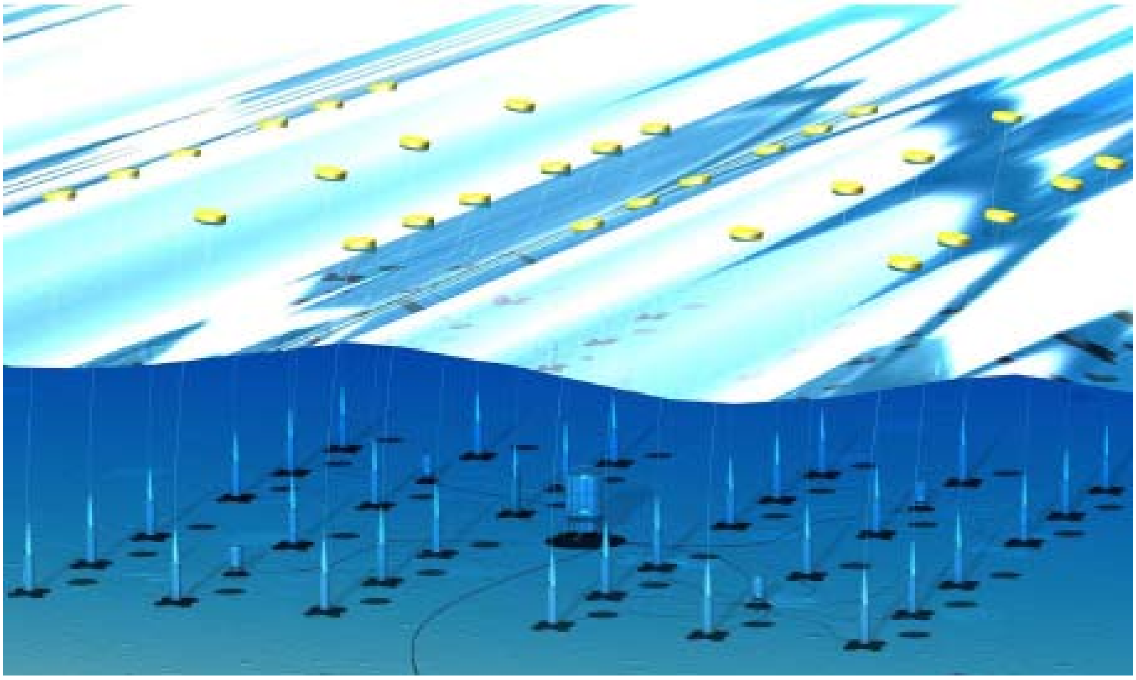


**FIGURE 2: AN ILLUSTRATION OF WHAT A WAVE POWER PLANT MIGHT LOOK LIKE IN THE FUTURE. © SEABASED INDUSTRY AB**

### 1.1.2 *Life Cycle Assessment*

Early attempts to reduce the strain caused by human activities on the environment consisted mainly of reducing point emissions of pollutants from industries, sewage plants and other facilities. The effectiveness of this approach proved to be limited. As environmental problems began to assume a global rather than local scale the need of a holistic perspective became evident. When developing an "environmentally friendly" product or service the whole life cycle must be studied. Life Cycle Assessment (LCA) is a method for quantitatively assessing the environmental impact caused by a product, an industrial process or a service throughout its entire life cycle –"from the cradle to the grave". For all stages of the life cycle, input of raw materials and energy is calculated as well as output of emissions and waste. The environmental impacts of these flows are then assessed. The goal may be to compare two products performing the same function, to decide between alternative production processes or develop an efficient system for recycling of packaging materials.

The first life cycle assessments were made as early as the late 1960s, but the use of LCA developed relatively slowly until the beginning of the 90s. In the late 80s the Society for Environmental Toxicology and Chemistry (SETAC) developed a framework for development and harmonization of the LCA methodology. One important application was the attempt to reduce the amount of waste deposition. In Sweden LCA-studies concerning different kinds of packaging materials provided a basis for legislation about producer responsibility.The use of LCA increased during the 90s and was applied by governments as well as corporations as basis for policies, product development and marketing. During this period the International Organization for Standardization (ISO) began developing a standardized description of the LCA methodology (2). Since 2006 the two ISO standards concerning LCA are ISO 14040 (Principles and framework) and ISO 14044 (Requirements and guidelines). Standardisation of LCA methodology and the compilation of LCI databases is making LCA an increasingly practicable tool for many different purposes. An increasingly important application of LCA is environmental product declarations, described further below.

### 1.1.3 *Environmental Product Declarations*

In order to facilitate environmental comparisons between products and thereby promote environmental improvement, an ISO standardization of what is called Type III environmental labelling was developed (3). Type III labels are environmental product declarations (EPD) containing quantified environmental information based on life cycle assessment performed according to the ISO standards 14040 and 14044. An EPD also provides additional environmental information such as impact on biodiversity and risk assessment on human health and environment. The ISO standard for EPDs is ISO 14025.

The implementation of ISO 14025 can differ, making comparison between EPDs problematic. To deal with this problem the EPD®system was developed in the late 1990s. In early 2008 a revised version of the system, the International EPD®system was launched. The system was initiated by industry and is managed by the International EPD Consortium

(IEC), a non-profit global network of interested parties. The Swedish Environmental Management Council (Miljöstyrningsrådet) has played an important part in the development of the EPD®system. The main objective of the system is to

> […] help and support organisations to communicate the environmental performance of their products (goods and services) in a credible and understandable way by
>
> - offering a complete programme for any interested organisation to develop and communicate EPDs according to ISO 14025, and
> - to support other EPD programmes (i.e. national, sectorial etc.) in seeking cooperation and harmonisation and helping organisations to broaden the use of their EPDs on an international market. (4)

The EPD®system regulates the implementation of the ISO standars for LCA and EPD through the General Programme Instructions (4). The instructions are supplemented by calculation rules specific for different product groups. These Product Category Rules (PCR) are developed by institutions involving LCA experts, companies and branch organizations in cooperation. To ensure the credibility and market acceptance of the EPD®system all EPDs developed within the system must be verified by an independent and accredited verifier. The EPD can then be registered and the EPD® logotype can be used.

## 1.2 Purpose

The electricity produced in a wave power plant does not stem from fossil fuels. However, this does not automatically mean that wave power is an "environmentally friendly" method for electricity production. The purpose of this master´s degree project is to conduct a life cycle assessment of electricity produced using Seabased´s wave power concept. The study aims at identifying parts of the life cycle causing large environmental impacts, thus representing possible areas of improvement.

The LCA will be performed according to the LCA methodology rules prescribed in the PCR for electricity production, developed within the International EPD® system (5). The results of the study will not be comparable to LCA results for other modes of electricity production based on mature technologies. However, as the technology develops from the prototype stage into commercially viable systems, the present work may be further developed, producing comparable results.

## 1.3 OUTLINE

Chapter 2 presents LCA methodology and important concepts. In chapter 3 the goal and scope of the present LCA study are defined. The studied system is described in chapter 4 and chapter 5 presents the methodology used for the study. The results of the study are presented in chapter 6 and further interpreted in chapter 7. In chapter 8, overall conclusions of the study are presented as well as an outlook on possible future work.

# 2 LCA CONCEPTS AND METHODOLOGY

Basically, conducting an LCA means gathering data about input and output flows of resources and emissions to and from a system, and then making a quantitative statement about the potential environmental impact of these flows. However, there are many ways to go about this and the results of the LCA will differ widely depending on the methodology used. This chapter gives a brief walk-through of LCA methodology and important concepts, mainly based on (2), (6), (7) and (8).

The ISO standard divides the LCA procedure into four phases:

1. Goal and scope definition
2. Inventory analysis
3. Impact Assessment
4. Interpretation

It is often emphasized that LCA is an iterative process and that the four phases cannot be seen as four steps to be performed one after another. The four phases are further described below.

## 2.1 GOAL AND SCOPE DEFINITION

Defining the goal and scope of an LCA study is very important, since it sets the conditions under which the study is performed. The goal of the study may be to compare the environmental performance of different products, to guide the design process of a new product or to find ways to reduce the environmental burden of a product or service. The LCA results may be used internally, e.g. as basis for "eco-design" or externally, for marketing or eco-labelling. The scope of the LCA project is then decided by the intended application of the study.
The scope is defined in terms of

- **functional unit** and **reference flow**
- geographical, technological and temporal coverage
- **system boundaries** and **allocation** methods
- choice of **elementary flows** and **environmental impact categories** to include in the study
- **cut-off rules**, data quality requirements, overall level of detail of the study

The **functional unit** of an LCA is the reference unit for the study, basically a clearly defined "amount" of the function performed by the studied system. For example, the environmental impacts of fuel production is often calculated per MJ of fuel energy content. The **reference flow** is the "amount" of the product system needed to produce the functional unit. The reference flow may be for instance the production of 0,02 liters of diesel, corresponding to 1 MJ fuel energy.

By geographical, technological and temporal coverage is meant a definition of which geographical region, technology and time period is reflected by the LCA. The data might for example reflect Swedish best available technology in the 1990s or the technology used at a specific production site in the year 2005.

**System boundaries** define processes included in the studied system. The choice of system boundaries will have great impact on the results of the LCA. The ideal system boundaries for a product system would be infinite, meaning that all processes associated to the system would be assessed in an infinite spatial and temporal perspective. Naturally, this is not possible and the system boundaries should be set so that all processes relevant in relation to the goal of the study are included.

**Allocation** of environmental burdens to different functions of a product system is an important part of the LCA methodology. For example a production process may result in more than one product and it must be determined which product(s) should bear which environmental burdens of the process. Combined heat and power (CHP) plants are typical examples, where the environmental burdens of the plant must be attributed to the heat and/or electricity production. Common allocation methods are

- allocation according to physical causal relationships, e.g. by mass
- allocation according to economical factors, e.g. by market value

The problem of multi-output processes can also be handled through system expansion. This means that the studied system is expanded to include all output products of the process. The functional unit could for instance be changed from "1 kWh of electricity produced in a CHP plant" to "1kWh of electricity and 2 kWh of heat produced in a CHP plant". This eliminates the need to allocate the ISO standards for LCA

**Elementary flows** are flows of resources, emissions and waste across the system boundary. In an LCA these flows are categorized into **environmental impact categories**, using characterization factors. For instance, the environmental impact category of global warming potential is expressed in carbon dioxide equivalents and all substances contributing to this impact category are multiplied by a characterization factor reflecting the relative global warming potential of the substance.

**Cut-off rules** prescribe a limit for excluding processes or flows that are of negligible importance to the study. A commonly used cut-off rule is the "1 percent-rule", stating that 99 percent of the mass flow, energy content and environmental impact of the product system shall be included in the study. In principle the only way to determine whether this criterion is fulfilled is of course to inventory all flows . In reality the cut-off rule is applied using estimations and expert judgement.

## 2.2 Inventory Analysis

The inventory analysis phase consists of identifying all processes included in the product system, collecting data for these processes, carrying out allocation and calculating the resulting flows of input and output. The main result of the inventory analysis is an inventory table listing the quantified elementary flows to and from the system. The scope definition phase and the inventory analysis phase are closely connected. The scope definition guides the data collection and calculations, but the relationship works both ways. For instance, the need for adjustment of e.g. system boundaries or allocation methods often appears during the inventory analysis phase. These first two phases of an LCA are often referred to as Life Cycle Inventory, LCI.

## 2.3 Impact Assessment

In this phase the final results of the LCA are obtained. The inventoried elementary flows are categorized into environmental impact categories, e.g. global warming potential, ozone depletion potential or non-renewable energy use. One substance can contribute to several impact categories. For instance, the release of nitrogen oxides can contribute to acidification as well as eutrophication.

Several methods have been developed to aggregate the potential environmental impact of a product system into a single impact category. The purpose of this is to obtain a single parameter for comparisons between product systems. In order to do this the result for each environmental impact category is weighted according to relative importance. Because of the obvious problems associated with objectively deciding which are the most important environmental impacts, weighting is rarely used in LCA today. Instead the LCA results are presented as potential environmental impacts by the different categories. Weighting is not used when preparing an EPD.

## 2.4 Interpretation

In the interpretation phase the results of the analysis, assumptions and choices made are evaluated and conclusions are drawn. The interpretation phase can consist of:

- consistency check
- completeness check
- contribution analysis
- sensitivity and uncertainty analysis

The purpose of a consistency check is to evaluate whether the assumptions, methods and data used in the analysis are consistent with the goal and scope of the LCA. In the completeness check it is determined whether all relevant processes and data are included in the study. The completeness check can for instance be performed by a technical expert.

Based on the results of these surveys the need for methodological changes or collection of more detailed data may be identified. In other words the LCA work must be evaluated continuously throughout the entire process.

## 2.5 LIMITATIONS OF LCA

An LCA does not give a complete picture of the environmental performance of a product or a service. First of all, an LCA does not take into account all environmental aspects of a product system. In particular, local effects on e.g. eco systems are not reflected in the results of an LCA. Also, the temporal or geographical context of emissions and resource use is generally not considered. For instance, the actual impacts caused by emissions of acidifying substances depend to a large extent on the characteristics of the recipient. The time span over which a pollutant is emitted may also be of importance, since the environment may be able to handle small emissions over a long period of time whereas a large single emission may cause considerably more damage.

When comparing products or services the choice of environmental impact categories will be very important for the results. When, for instance, comparing nuclear power to other power production methods, the aspect of radioactive waste should probably be included to produce a "fair" result. Then there is also the problem of deciding which environmental impact is the most important.

The results of an LCA depend very much on system boundaries and other methodological aspects. This means that two LCAs for the same product may show very different results. This is a problem that has received considerable attention. Through standardization and database development the aim is to make LCA a reliable tool for e.g. product development and policy choices.

# 3 Goal and scope

## 3.1 Goal

The overall purpose of this LCA is to increase the knowledge of the environmental performance of the wave energy conversion system developed by Seabased Industry AB. The main intended application of the study is

- support for product development (choice of materials, production methods, etc.)
- to provide a basis for future environmental product declaration
- commercial and public information

The LCA is performed according to the LCA methodology rules of the International EPD® system. The governing documents are the **Product Category Rules for preparing an EPD for electricity production** (5) and the **EPD General Programme Instructions** (4) with **supporting annexes** (9), (10), henceforth referred to as the PCR, GPI and GPI Annexes respectively. Deviations from the PCR are mostly due to the fact that the studied system does not yet exist, and are described in chapter 3.2 below.

## 3.2 Scope

### *3.2.1 Functional Unit and Reference Flow*

The functional unit used in this LCA is **1 kWh net of electricity from wave power produced and delivered to the grid.** By "1 kWh net" is meant that electricity used for operation of the system is subtracted from the total amount of electricity produced. The reference flow is the construction, operation and end-of-life phase of the corresponding fraction of a wave power plant with a rated power of 20 MW, as described in chapter 4.

### *3.2.2 Geographical, Temporal and Technological Coverage*

The LCA will reflect a wave power plant constructed in the near future. The plant is assumed to be placed off the coast of Sweden or Norway and the production of the plant is assumed to take place in Lysekil. Thus the LCA reflects Scandinavian/Swedish conditions. Data regarding production of raw materials, semi-finished products and components reflect the geographical region where the processes are assumed to take place.

About temporal coverage the PCR states that for the operational phase "data shall reflect one reference year or an annual average of a defined reference period". Since the studied system does not yet exist, data concerning electricity consumption, maintenance, availability and annual production of the plant is based on calculations and estimations.

The PCR also states that data shall reflect the technology actually used, which in this case translates into technology that is planned to be used. The estimated technical life of the wave power plant is twenty years. During this period technologies used in e.g. maintenance, dismantling and waste treatment are expected to differ from those used today. However, speculations about future technology development would present very large uncertainties. Thus the system studied is a wave power plant constructed, operated and dismantled using present technology.

### *3.2.3 System Boundaries*

The LCA includes the full life cycle of a wave power plant, consisting of 1000 generators and point absorbers (buoys), marine substations and sea cable, from the extraction of raw materials to the disposal of waste. The life cycle is divided into upstream processes, operational phase and downstream processes.

Upstream processes include

- extraction and transportation of raw materials
- production and transportation of semi-finished products (e.g. steel profiles)
- manufacturing and transportation of components
- manufacturing of and reinvestment in wave energy converters and sea cables
- deployment of the plant
- transportation and treatment (deposit/destruction) of waste generated in upstream processes

Operational phase includes

- operation and maintenance of the plant
- transmission of electricity to grid

Downstream processes include

- dismantling of wave energy converters, transportation and deposit/destruction of waste

Processes excluded from the life cycle are:

- manufacturing of marine substations (switchgear, transformers)
- construction, reinvestment and dismantling of buildings and machines (capital goods) used in the included processes
- accidents and breakdowns

System boundaries are shown in a simplified process tree in figure 3.

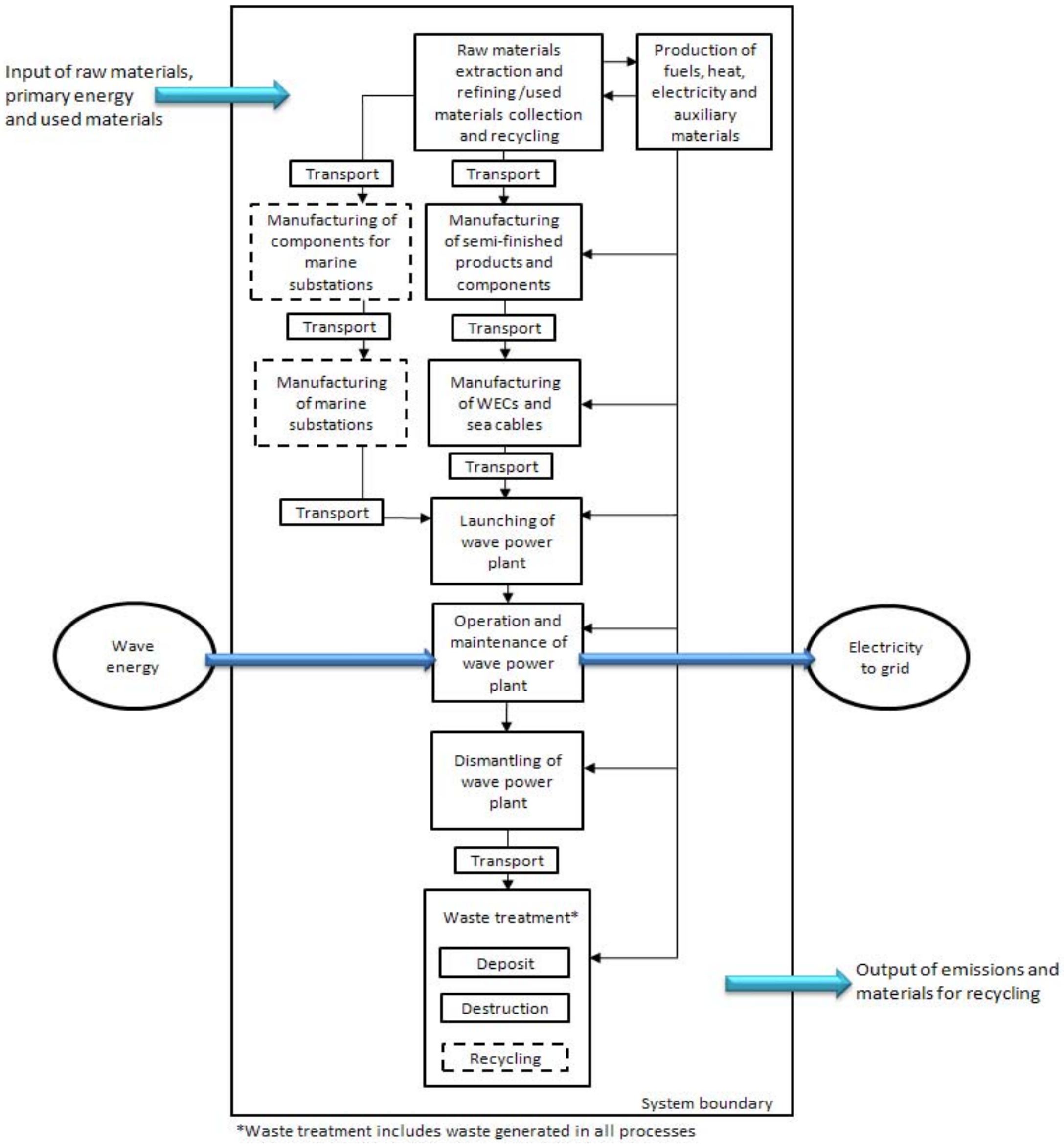



**FIGURE 3: SIMPLIFIED PROCESS TREE WITH SYSTEM BOUNDARIES. SOLID LINES INDICATE INCLUDED PROCESSES WHEREAS DASHED LINES INDICATE PROCESSES EXCLUDED FROM THE STUDY. WASTE TREATMENT PROCESSES ARE INCLUDED FOR WASTES PRODUCED BY ALL INCLUDED PROCESSES.**

Geographical and temporal boundaries and boundaries towards nature are defined as follows:

- No geographical boundary is set, meaning that emissions and inputs to and from nature and other technical systems are included disregarding geographical location.
- The temporal boundary for emissions to air and surface water from landfills is 100 years, since emissions after that time are considered negligible. Regarding emissions to groundwater no temporal boundary is set, meaning that long-term emissions are included in the inventory. All other inputs and outputs to and from the system are included disregarding when they take place.
- All emissions to nature from included processes and all inputs from nature are included.

### *3.2.4 Allocation*

The ISO standards for LCA recommend the use of system expansion as allocation method. The EPD® approach differ from the ISO standards in this respect. The PCR prescribe the use of allocation based on physical causal relationships. In the present study no allocation is needed regarding foreground data (all environmental impact of the wave power plant is allocated to the produced electricity).  In the background data used (e.g. raw materials extraction) allocations are sometimes necessary. Background data calculated using system expansion is avoided as far as possible. If system expansion causes negative flows of e.g. emissions in background data these flows are set to zero, as prescribed in the PCR.

The approach used regarding waste and reused or recycled materials is important to define since it will have great impact on the results of an LCA study. It is basically a question of defining where materials enter and leave the studied system.  The EPD guide lines prescribe using the "Polluter Pays" approach, which designates the environmental burden of waste as follows:

- The environmental impact connected to the treatment of wastes not being used by any subsequent user rests with the generator of the waste – hence, the waste is not considered as a resource.
- The environmental impact connected to the processing of the waste into a resource for a subsequent user rests with the user of the resulting resource (1).

The "Polluter Pays approach" is further illustrated in figure 3 by describing the handling of different types of wastes, worn-out products and output flows. Figures 4 and 5 specifically describe the PP allocation method applied to waste incineration and recycling respectively.

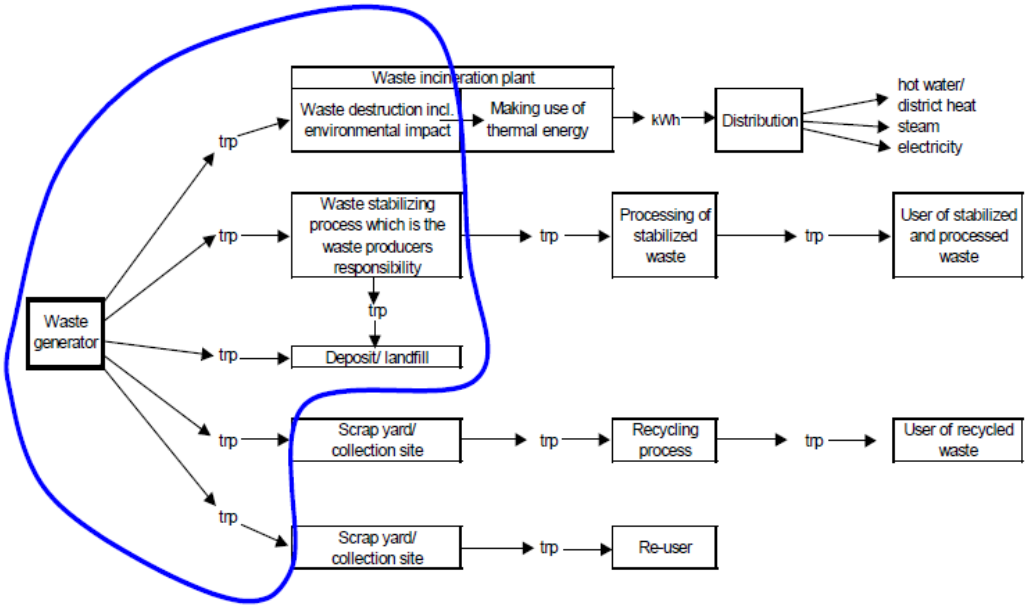



**FIGURE 4: THE "POLLUTER PAYS" PRINCIPLE ILLUSTRATED FOR VARIOUS TYPES OF WASTE TREATMENT OPTIONS. THE ENCIRCLED AREA INDICATES THE ENVIRONMENTAL IMPACT THAT HAS TO BE CARRIED BY THE WASTE GENERATOR (9).**

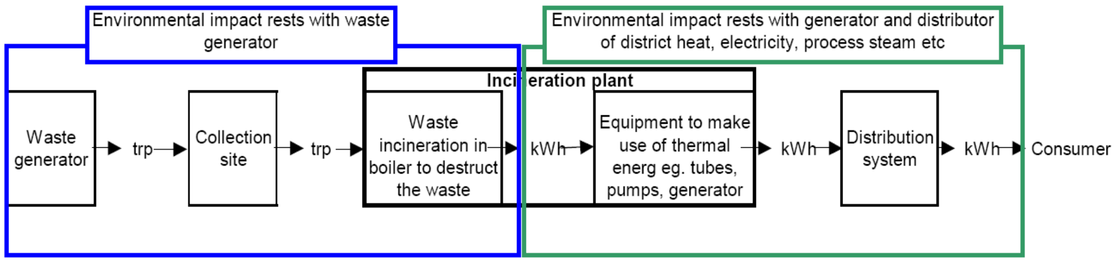



**FIGURE 5: THE "POLLUTER PAYS" PRINCIPLE APPLIED TO WASTE INCINERATION AND RESULTING ENERGY PRODUCTS. ALL EMISSIONS DUE TO WASTE INCINERATION ARE ALLOCATED TO THE WASTE DESTRUCTION FUNCTION OF THE INCINERATION PLANT (9).**

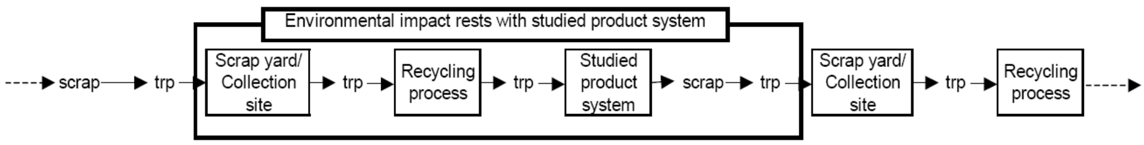



**FIGURE 6: THE "POLLUTER PAYS" PRINCIPLE APPLIED TO INPUTS OF RECYCLED MATERIALS AND OUTPUTS OF MATERIALS THAT WILL BE RECYCLED. USED MATERIALS ENTER AND LEAVE THE STUDIED SYSTEM AT THE SCRAP YARD/COLLECTION SITE. THUS USED MATERIALS AND SCRAP FOR RECYCLING RESPECTIVELY REPRESENT INPUT AND OUTPUT FROM THE SYSTEM. NO ENVIRONMENTAL BURDENS FROM EARLIER LIFE CYCLES OR CREDITS FOR CONSEQUENT LIFE CYCLES ARE ASSIGNED TO THE STUDIED SYSTEM (9).**

### 3.2.5 *Environmental Impact Categories*

The choice of environmental impact categories is done according to the PCR. Impact categories are divided into material use and potential environmental impact.

Material use includes:

- **Non-renewable resources**

  - Material resources

  - Energy resources (used for energy conversion purposes)

- **Renewable resources**

  - Material resources

  - Energy resources (used for energy conversion purposes)

- **Water use**

Potential environmental impact includes:

- **Emission of greenhouse gases** (expressed as the sum of global warming potential, GWP, 100 years, in $CO_2$ equivalents).

- **Emission of ozone-depleting gases** (expressed as the sum of ozone-depleting potential in CFC 11-equivalents, 20 years).

- **Emission of acidifying gases** (expressed as the sum of acidifying potential in $SO_2$ equivalents).*

- **Emission of gases that contribute to the creation of ground-level ozone** (expressed as the sum of ozone-creating potential, ethene-equivalents).

- **Emission of substances to water contributing to oxygen depletion** (eutrophication, expressed as the sum of oxygen consumption potential in $PO_4$ equivalents)*

Characterization factors used in the study are prescribed in GPI Annex B and presented in appendix 3. These characterization factors are widely accepted and used within the scientific community. *Regarding acidification and eutrophication potential the GPI prescribes that the potential be presented as mol H+ and kg O2 respectively. However, the characterization factors given relate the listed substances to $SO_2$- and $PO_4$-equivalents.

### 3.2.6 *Cut-off Criteria*

The general rule for omitting inventory data of negligible relevance to the study is that for the overall inventory results 99% of the elementary flows regarding mass, energy content and environmental impact shall be included in the LCA.

### 3.2.7 *Data Quality Requirements - Specific and Generic Data*

The GPI classifies data into three categories:

- **specific data** are data gathered from actual production sites and product-specific processes.
- **selected generic data** are data from commonly available sources, prescribed by the PCR, fulfilling prescribed characteristics regarding reference year, cut-off criteria, completeness and representativeness
- **other generic data** are data from other generic data sources

The GPI states that environmental impact associated with other generic data must not exceed 10% of the total environmental impact. According to the PCR, generic data (selected or other) should not be older than 10 years. Specific data shall be used if available. For the operational phase, data shall always be specific. Since no full-scale wave power plants yet exist, the present LCA study is performed for a "typichal" plant, as it is planned to be designed, constructed and operated.

Specific data is used for

- material composition of the wave power plant
- some transportation distances
- deployment and dismantling of the plant (consumption of ship fuel)
- maintenance processes and reinvestment rates

Generic data is used for

- manufacture of construction- and auxiliary materials (such as fuels, lubrication oil etc.)
- some transportation distances
- transportation services (fuel use and emissions in conjunction with transportation)
- waste treatment processes
- regional mixes for electricity generation
- resource use and emissions in conjunction with electricity used during the construction/reinvestment/dismantling processes

# 4 System description

## 4.1 Description of Wave Energy Converter

A wave energy converter of the studied type consists to a large part of steel and iron. The translator body is made of cast iron whereas the buoy, the wire, the stator, the support structure and the casing is mainly made of various types of steel. The permanent magnets on the translator are made of a neodymium-iron-boron alloy (about 24, 75 and 1% respectively). The stator cables consist of copper wire insulated with cross-linked polyethylene (PEX). The wave energy converter is attached to a foundation. The design and material for the foundation is a matter under discussion. For the prototypes made so far, armed concrete foundations have been used and this type of foundation is also assumed to be used in the present study.

## 4.2 Plant Layout

No wave power plants of the studied type yet exist. Further, the work with designing wave energy converters for serial production is not completed. Hence, this LCA is conducted for a hypothetical wave power plant (WPP) consisting of "prototype" generators. In reality the design of generators used in full scale WPPs is expected to be considerably "slimmed down", thus increasing the material efficiency and environmental performance of the technology.

The studied WPP consists of 1000 generators, placed in arrays of 50 units. Each array is connected by a sea cable to a low voltage marine substation (LVMS) which in turn is connected to a medium voltage substation (MVMS). In the LVMS, the irregular power from the generators is converted into a DC voltage and then into a smooth, three-phase AC voltage. The voltage is then transformed to 12 kV in the LVMS and further to 36 kV in the MVMS. From the MVMS the power from the generators is transmitted by a sea cable to the electrical grid on shore. The distance from the WPP to the grid is assumed to be 10 km. Figure 7 is a schematic diagram of the electrical system of a plant.

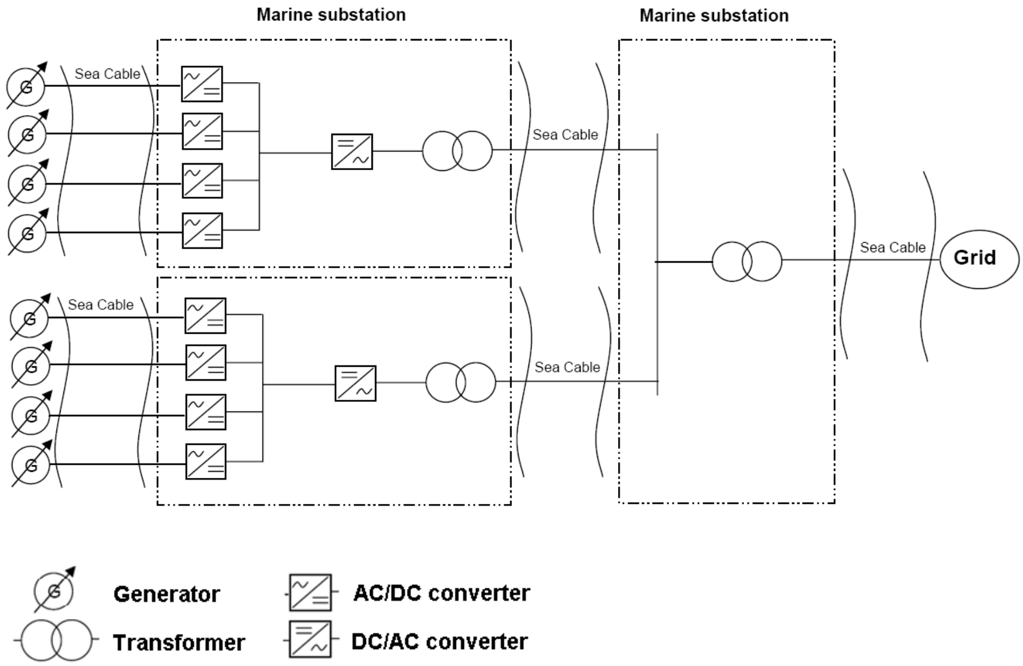



**FIGURE 7. SCHEMATIC IMAGE OF THE ELECTRICAL SYSTEM OF A WPP (1).**

## 4.3 Electricity Production

The energy delivered to the grid $E_{grid}$ from a wave power plant is calculated as follows:

$$E_{grid} = J_{avg} \times D \times Abs \times \eta_{gen} \times Av \times \eta_{trans} \times N \times Life \times 8760 \ \ [kWh]$$

where

$J_{avg}$ = average power flow of the waves [kW/m wavefront]

D = buoy diameter [m]

Abs = average power absorption rate

$\eta_{gen}$ = generator efficiency

Av = availability factor

$\eta_{trans}$ = transmission efficiency

N = number of WECs

Life = technical service life of the WPP [years]

The power absorption rate is the percentage of the incoming power flow that is absorbed by the buoy. The availability factor stems from the assumption that all WECs are not functioning 100% of the time. The transmission efficiency is the efficiency of the marine substations and sea cables transmitting the electricity to the on shore grid connection .

## 4.4 DESCRIPTION OF STUDIED CASES

Two cases, referred to as Case NO and Case SE, are studied. The two cases reflect a wave power plant operating off the coast of Norway and Sweden respectively. The parameter values shown in table 1 are the same for both cases. The total delivered energy and reference flows corresponding to the functional units are presented for the two cases in table 2.

The average power flow of the waves and the distance from the production site in Lysekil to the WPP site is different for the two cases. The two cases also differ in that a larger ship is assumed to be used to transport the WECs to the plant site in the Norwegian case. This means that the ship is able to carry a larger number of WECs, thus needing fewer trips to and from Lysekil, but also that the fuel consumption of the ship is larger.

- **Case NO** is a WPP (as described above) operating in a location with an average wave climate of 20 kW/meter wavefront. This wave climate can be found off the coast of Norway, at least 400 km by ship from Lysekil. The distance used in the study is 650 km. The ship used for transport to the WPP site is assumed to carry 100 WECs at a time and to consume 30 tons of marine diesel oil per day (24h). The average power absorption rate is assumed to be 12,5%.

- **Case SE** is a WPP operating in a relatively poor wave climate, with an average power flow of 5 kW/meter wavefront. This wave climate is found off the Swedish west coast, near Lysekil. The distance for ship transportation used in the study is 30 km. The ship used for transport to the WPP site is assumed to carry 40 WECs at a time and to consume 20 tons of marine diesel oil per day (24h). The average power absorption rate is assumed to be 15%.

The power absorption rate is an important factor and is difficult to estimate. The absorption depends on the wave period (the time between two wave crests) as well as generator design and load properties. The absorption decreases with longer wave periods. The power flow of the waves are proportional to the wave period times the square of the wave height, meaning that a larger power flow generally means longer wave periods and lower absorption rates. This is one of the reasons why the absorption rate is lower in the Norwegian case.

The generators used in a wave power plant will be designed for the wave climate of the plant site. However, at the present stage only one complete generator design exists and this design is used for both cases in the study. This generator is designed for the Swedish west coast. To reflect this, the absorption rate is adjusted a bit further downwards for the Norwegian case.

**TABLE 1: PARAMETERS USED TO CALCULATE ENERGY OUTPUT FROM A WPP, USED IN CASES NO AND SE**

| Parameter | Value |
|---|---|
| Number of WECs | 1000 |
| Buoy diameter | 4 m |
| Generator efficiency | 85 % |
| Availability factor | 99 % |
| Power consumption for operation of WPP | 40 kW |
| Estimated technical life of WEC | 20 years |
| Distribution efficiency | 95 % |

**TABLE 2: TOTAL DELIVERED ENERGY AND REFERENCE FLOWS CORRESPONDING TO THE FUNCTIONAL UNIT**

| | Case NO | Case SE |
|---|---|---|
| Delivered energy to grid [TWh/WPP] | 1,33 | 0,395 |
| Reference flow [WPP/kWh to grid] | $7{,}52\times10^{-10}$ | $2{,}53\times10^{-9}$ |

## 4.4 Deployment, Maintenance and Dismantling of the Plant

The manufacturing of the wave power plant will take place at the seaside in Lysekil and the WECs will be loaded directly onto a specially built ship that will carry them to the WPP site for deployment. Deployment of the plant is estimated to take two hours per WEC. Each WEC is also assumed to need on average two hours of maintenance work and one replacement of the wire rope throughout its lifetime. Dismantling of the plant will basically be done by the same procedure as the deployment.

# 5 METHODOLOGY

## 5.1 DATA COLLECTION

### *5.1.1 BACKGROUND DATA*

Life cycle inventory data for materials/semi-finished products (e.g. copper wire, steel profiles), construction and dismantling services, transports and waste treatment are generic data collected from the sources listed in table 3, along with references for more information about the data. The data sources are further described in appendix 1. In some cases other sources than those prescribed in the PCR were used. This was done mainly because data for some materials and processes were not provided by the prescribed data sources.

**TABLE 3: BACKGROUND DATA SOURCES. *OTHER THAN PRESCRIBED IN THE PCR**

| Material/process | Source | Reference |
|---|---|---|
| ***Metals*** | | |
| Aluminium | European Aluminium Association | (11) |
| Copper wire | Deutsches Kupferinstitut | (12) |
| Neodymium | Ecoinvent | (13) |
| Steel/iron | Worldsteel | (14) |
| Stainless steel | World stainless | (15) |
| Zinc | Ecoinvent | (16) |
| Other | Ecoinvent | (17) |
| ***Concrete*** | Ecoinvent | (18) |
| ***Plastics and rubber*** | | |
| ABS | PlasticsEurope, through Ecoinvent | (19) |
| EPDM rubber | Ecoinvent* | (20) |
| EVA | Ecoinvent* | (20) |
| GAP (Glass fibre reinforced plastic) | Ecoinvent* | (18) |
| Polyethylene (HDPE, PEX, LDPE, LLDPE) | PlasticsEurope, through Ecoinvent | (20) |
| Polyamide 6 | PlasticsEurope, through Ecoinvent | (20) |
| Polypropylene | PlasticsEurope, through Ecoinvent | (20) |
| Polyurethane | Ecoinvent* | (20) |
| ***Chemicals*** | | |
| Lubricating oil | Ecoinvent* | (13) |
| Paints | Ecoinvent* | (13) |
| Other chemicals | Ecoinvent* | (13) |
| ***Other materials*** | Ecoinvent | (17) |
| ***Transports*** | | |
| Road | NTM, Nätverket för Trafik och Miljön | (21) |
| Rail | NTM/Ecoinvent* | (21)/ (22) |
| Air | Ecoinvent* | (22) |
| Sea | Ecoinvent* | (22) |
| Production of ship fuel | Ecoinvent | (23) |
| Combustion of ship fuel | SMED, Svenska MiljöEmissionsData | (24) |
| ***Electricity*** | Ecoinvent (electricity mixes from IEA) | (25) |
| ***Manufacturing processes*** | | |
| Cleaning and blastering of cast iron | CPM LCA database* | (26) |
| Other manufacturing processes | Ecoinvent | (16), (20),(27) |
| ***Waste treatment processes*** | Ecoinvent | (28) |

### 5.1.2 *Ecoinvent LCI Database*

The Ecoinvent LCI database is prescribed in the PCR as source for selected generic data for a number of materials and processes. The database was developed by the Swiss Centre for Life Cycle Inventories, which is a cooperation between a number of Swiss LCA institutions. The database contains about 4000 datasets for products, services and processes, presented as national, regional or global averages. The Ecoinvent methodology is based on a modular approach, and data are neither aggregated horizontally nor vertically, meaning that different processes producing the same output are presented separately, as are subsequent steps in a process chain. System expansion is not used in the Ecoinvent data. More information on the Ecoinvent database can be found in (17).

Most data in the Ecoinvent database reflect average European conditions. An important exception is electricity production, for which data is provided by country and by voltage level. For manufacturing processes that are assumed to take place in Sweden the electricity mix used in the Ecoinvent processes was changed to the Swedish electricity mix. For a few processes assumed to take place in Germany the German electricity mix was used, whereas the average European electricity mix was used for processes taking place in an unknown (European) location.

### 5.1.3 *Material Composition*

The material composition of components produced specifically for the wave power plant (most of the WECs, casing and support structures in marine substations) has mainly been derived from CAD drawings. In most cases component weights were given in the drawings (calculated by the CAD program). Some weights were calculated manually based on dimensions and material densities. For off-the -shelf components (wire ropes, sea cables, electrical components in marine substations) the material content was calculated and/or estimated from data in product sheets.

Amounts of materials removed by milling and drilling are estimations based on drawings. When such estimations where not possible a standard amount from Ecoinvent was used (0,23 kg metal removed by milling per kg finished product).

### 5.1.4 *Transports*

Figure 8 shows an overview of the transports included in the LCA. Transportation distances for semi-finished products and components to the WEC production site were estimated in the cases where the production site is known. In other (quite numerous) cases, standard distances were used. The distances were taken from the Ecoinvent Overview and Methodology report (17), with the exception of an adjustment upwards of the transport distance of semi-finished steel products, done to reflect the geographical location of Swedish and European steel works in relation to Lysekil. The distances are shown in table 4.

All background data for materials and semi-finished products include transports to the European production site or regional storage. For the transport from these sites to component manufacturing sites the standard distances in table 4 have been used. Regarding transportation of waste to scrap yards, deposit or incineration sites the standard distance 100 km has been used for all materials.

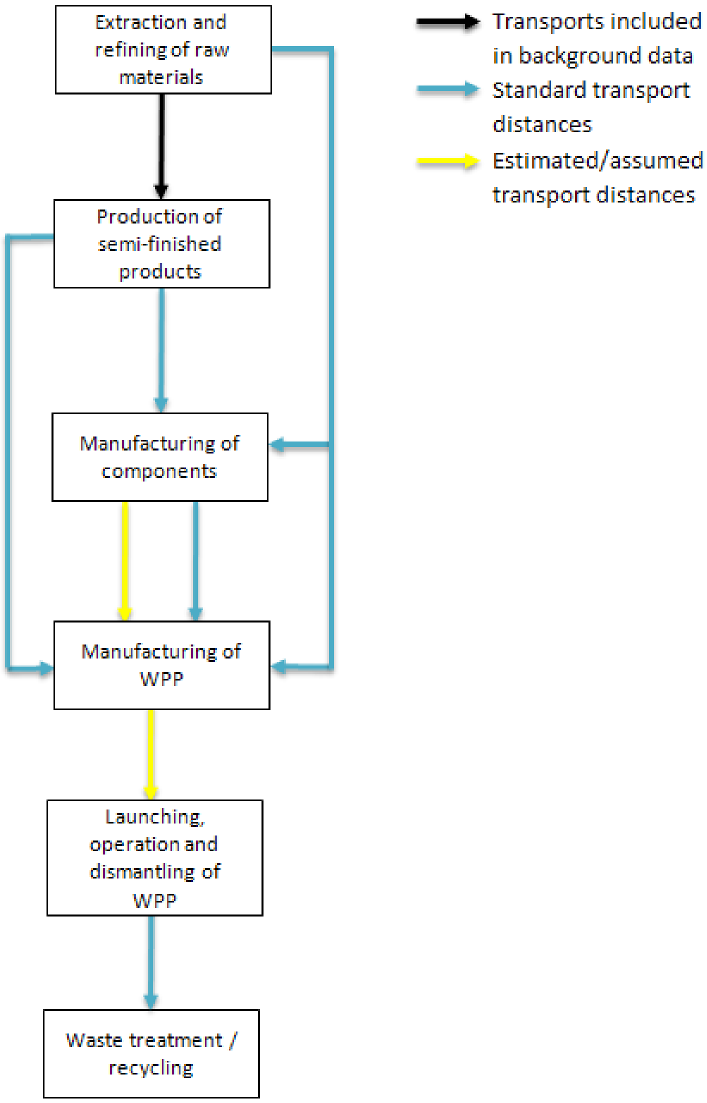



**FIGURE 8: OVERVIEW OF TRANSPORTATION DISTANCES USED IN THE LCA**

**TABLE 4: STANDARD TRANSPORTATION DISTANCES USED FOR MATERIALS, SEMI-FINISHED PRODUCTS AND COMPONENTS FOR USE IN EUROPE.**

| Material | Train [km] | Lorry [km] |
|---|---|---|
| Chemicals | 600 | 100 |
| Concrete | - | 50 |
| Steel | 350 | 150 |
| Other metals | 200 | 100 |
| Nitrogen | 200 | 100 |
| Plastics | 200 | 100 |

The  prescribed data source for transports is NTM (Nätverket för trafik och miljön / Swedish Network for Traffic and the Environment) or regional alternatives.  NTM provides transport data reflecting Swedish conditions. The NTM data for road transport (lorry) was assumed to reflect average European conditions and was used for all road transport. Regarding transport by train the mix of electro traction and diesel engines as well as the electricity production mix varies widely between countries. Therefore NTM data was used for transports within Sweden whereas data for European rail transports was taken from the Ecoinvent database. Data for intercontinental air and sea transport (used for import of some components) was also taken from Ecoinvent.

### *5.1.5 SHIP OPERATIONS*

The transport of the WECs and other components to the WPP site is assumed to be done using a ship built especially for this purpose and the ship is not assumed to carry any other cargo when returning to Lysekil. The NTM data, which is based on average utilization levels of freight ships, is therefore not directly applicable. The source used in the present study is a report from Svenska MiljöEmissionsData (SMED) (24), which is one of the data sources used by NTM. The data is given per ton of consumed fuel. Data on speed and fuel consumption per hour for a ship that may be used was provided by the shipping company. The fuel consumption as well as the emission factors differ between the transportation phase and the working phase and this is reflected in the data. In the Norwegian case the fuel consumption rate for transportation was approximated by fuel consumption rates for larger cargo ships.

### *5.1.6 APPROXIMATIONS AND SIMPLIFICATIONS*

The following approximations were made because of lacking data:

- Production of cast iron was approximated by production of secondary steel (produced from steel scrap in an electric arc furnace).
- All stainless steel grades have been approximated by data for grade 316 stainless steel.
- Drawing of aluminium wire (for transformers) was approximated by extrusion of aluminium profiles.
- Cold forming of steel dished ends was approximated by cold rolling of steel.
- The data for copper wire was given per meter of wire with a cross-section area of 1 $mm^2$. The environmental impact of copper wire was assumed to be equally large per kg of wire regardless of the wire size.
- NdFeB magnets material composition and production (through a sintering process) was approximated by the production of neodymium oxide and iron sinter.
- The process of extruding plastic insulation on to conductors was approximated by extrusion of plastic pipes.
- Crosslinked polyethylene (PEX) was approximated by high-density polyethylene (HDPE, from which PEX is made).

- Cutting of stator steel sheets and manufacturing of dummy loads, bearings, nuts and bolts have been approximated by the Ecoinvent process "steel product manufacturing" including resource consumption and emissions from an average metal working machine.
- The material composition of some electrical components has been approximated by the material composition of a circuit breaker (31).

Simplifications made in the study mainly concern manufacturing processes. For instance, the production of cables only include the processes of producing copper wire, extruding plastics on to the wire, drawing and zink coating of steel wire (for reinforcement). The manufacturing of WECs from semi-finished products include the following processes:

Cleaning and blastering (steel, cast iron)
Cold forming (steel pressure vessel heads)
Cutting (stator steel sheets, approximated by "steel product manufacturing")
Drilling (steel, cast iron, aluminium)
Extrusion (plastics, rubber)
Milling (steel, cast iron)
Manufacturing of dummy loads, bearings, nuts and bolts (approximated by "steel product manufacturing")
Pipe drawing (production of seamless steel pipes)
Welding (steel)
Wire drawing (production of steel wire from wire rod)
Zink coating (steel)

For launching, maintenance and dismantling processes only the production and combustion of marine diesel oil is considered. Processes excluded from the study are deemed to be of negligible importance for the results.

## 5.2 SimaPro LCA software tool

The life cycle of the WPP was modelled using the SimaPro LCA software tool. SimaPro was developed by the Dutch consultant company PRé Consultants and is one of the most widely used LCA software tools. The SimaPro license includes the Ecoinvent database, which was one of the main reasons for the choice of software.

SimaPro is based on a modular approach to LCA, using unit processes representing a quantitative amount of output from a process. Each unit process contains input from nature or technosphere (other unit processes) and output of products and emissions. The unit process can also contain output of waste for treatment, which is linked to waste treatment unit processes. For instance, the unit process “Hard coal, burned in industrial furnace” represents the environmental impact from the combustion of 1 MJ of hard coal. Emissions from the combustion are included as elementary flows, whereas the coal production is included as 0,035 kg of the unit process “Hard coal mix, at regional storage”. The use of electricity and transports are included as corresponding amounts of unit processes. The combustion process also includes the disposal of hard coal ash, represented by 0,0029 kg of the unit process “Disposal of hard coal ash to residual material landfill".

The elementary flows to and from the unit processes are characterized into environmental impact categories using characterization factors defined in the chosen environmental impact assessment method. The assessment methods can be modified by the user. The system of unit processes, is represented in a process tree or network. The relative or absolute contribution of each unit process to the various environmental impact categories can be seen in the network or in a process contribution table. The resulting elementary flows are presented in an inventory table. The software also provides the possibility to compare processes or systems and by using parameters different scenarios can be modelled.

With SimaPro uncertainty calculations can be carried out using Monte Carlo analysis. Monte Carlo analysis is a statistical method for assessing the combined variation of data points added together, each with different standard deviations. For each data point a mean value, a coefficient of variance and a statistical distribution is given. A random value within the defined distribution interval is generated for all data points, resulting in a new value for the sum of the data points. By repeating this process *n* times a data set consisting of *n* values for the sum is obtained. The mean value and standard deviation of this data set is then calculated. More information on SimaPro can be found in (32) and at the PRé Consultants website (33).

## 5.3 Uncertainty Estimations

Most of the data in the Ecoinvent database is supplied as a mean value with a log-normal distribution defined by the square of the geometric standard deviation. The 95% confidence interval is then obtained by multiplying or dividing the mean value with the geometric standard deviation. However, in many cases the data sources have not provided any uncertainty data and instead a simplified standard procedure has been used to quantify the uncertainty of this data. A qualitative assessment of the data quality was made using a pedigree matrix (see table 5), giving the data an indicator score for each of six characteristics: reliability, completeness, temporal correlation, geographical correlation, further technological correlation and sample size. The indicator scores were then translated into uncertainty factors (table 6) based on expert judgement. Further, a basic uncertainty factor (table 7) was assigned to each data point depending on the type of input or output. These factors are also based on expert judgement and derive from the fact that some flows show larger variations. For instance, emissions of $CO_2$ from a combustion process can be calculated quite accurately from the carbon content of the fuel, whereas emissions of heavy metals or CO are largely dependent on combustion properties. These seven uncertainty factors are then combined to calculate the square of the geometric standard deviation ($SD^2$) through the following formula:

$$SD^2 = e^{\sqrt{(\ln U_1)^2 + (\ln U_2)^2 + (\ln U_3)^2 + (\ln U_4)^2 + (\ln U_5)^2 + (\ln U_6)^2 + (\ln U_b)^2}}$$

where

$U_1$ = uncertainty factor of reliability

$U_2$ = uncertainty factor of completeness

$U_3$ = uncertainty factor of temporal correlation

$U_4$ = uncertainty factor of geographical correlation

$U_5$ = uncertainty factor of further technological correlation

$U_6$ = uncertainty factor of sample size

$U_b$ = basic uncertainty factor

**TABLE 5: PEDIGREE MATRIX USED TO EVALUATE DATA QUALITY, ADAPTED FROM (17).**

| Indicator score | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Reliability** | Verified data based on measurements | Verified data partly based on assumptions OR non-verified data based on measurements | Non-verified data partly based on qualified estimates | Qualified estimate (e.g. by industrial expert); data derived from theoretical information (shoichiometry, enthalpy, etc.) | Non-qualified estimate |
| **Completeness** | Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations | Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations | Representative data from only some sites (<<50%) relevant for the market considered OR >50% but from shorter periods | Representative data from only one site relevant for the market considered OR some sites but from shorter periods | Representativeness unknown or data from a small number of sites AND from shorter periods |
| **Temporal correlation** | Less than 3 years of difference from the reference period | Less than 6 years of difference from the reference period | Less than 10 years of difference from the reference period | Less than 15 years of difference from the reference period | Age of data unknown or more than 15 years of difference to the reference period |
| **Geographical correlation** | Data from area under study | Average data from larger area in which the area under study is included | Data from smaller area than area under study, or from similar area | | Data from unknown or distinctly different area |
| **Further technological correlation** | Data from enterprises, processes and materials under study (i.e. identical technology) | | Data on related processes or materials, but same technology, OR data from processes and materials under study but from different technology | Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology | Data on related processes or materials but on laboratory scale of different technology |
| **Sample size** | >100, continous measurement, balance of puchased products | >20 | >10 | ≥3 | Unknown |

TABLE 6: DEFAULT UNCERTAINTY FACTORS TO BE COMBINED WITH THE PEDIGREE MATRIX (17).

| Indicator score | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Reliability | 1,00 | 1,05 | 1,10 | 1,20 | 1,50 |
| Completeness | 1,00 | 1,02 | 1,05 | 1,10 | 1,20 |
| Temporal correlation | 1,00 | 1,03 | 1,10 | 1,20 | 1,50 |
| Geographical correlation | 1,00 | 1,01 | 1,02 | | 1,10 |
| Further technological correlation | 1,00 | | 1,20 | 1,50 | 2,00 |
| Sample size | 1,00 | 1,02 | 1,05 | 1,10 | 1,20 |

TABLE 7: BASIC UNCERTAINTY FACTORS (17).

| | Basic uncertainty factor |
|---|---|
| ***Input*** | |
| Thermal energy, electricity, semi-finished products, working material, waste treatment services, primary energy carriers, metals, salts | 1,05 |
| ***Transport services*** | 2 |
| ***Emissions to water*** | |
| COD, inorganic compounds (NH4, PO4, NO3, Cl, Na etc.) | 1,5 |
| PAH | 3 |
| Heavy metals | 5 |
| ***Emissions to air*** | |
| CO2, SO2 | 1,05 |
| NMVOC, Nox, N2O, CH4, NH3 | 1,5 |
| Particulates, PAH | 3 |
| CO, heavy metals | 5 |
| Other inorganic emissions | 1,5 |

The data sources used in the present study for steel and copper products do not provide any uncertainty data. Therefore the pedigree matrix method used by Ecoinvent has been applied to assess the uncertainty of this data. The pedigree matrix and uncertainty factors used are the same as those used by Ecoinvent , shown in tables 5-7 . The indicator scores given the data sets for steel products were (2,2,2,1,1,1) and for copper wire (2,2,2,1,3,1). The higher value of the "further technological correlation" uncertainty factor for copper wire stems from the fact that the environmental impact per kg of wire is assumed to be the same for all wire sizes.

Regarding standard transportation distances Ecoinvent uses the value of 2,09 for the square of the geometrical standard deviation. The same value was used when standard distances were used in the present study. The uncertainty regarding fuel consumption for ship operations was modelled as a uniform distribution with minimum and maximum deviating by 20% from the mean.

In the Monte Carlo analysis of the final results 1000 calculations were done for each impact category. The resulting uncertainty reflects uncertainties in background data and does not take into account uncertainty due to lacking data or any uncertainty in foreground data such as e.g. material composition. Also, no uncertainty of the characterization factors used is considered.

# 6 Results

## 6.1 Inventory Analysis

Table 8 shows the amounts of materials used per wave energy converter and per wave power plant. Besides the large amounts of concrete used for foundations, steel constitutes the main part of the constructions. The wave energy converters contribute to almost 99% of the total material flows of a wave power plant.

**TABLE 8: AMOUNTS OF MATERIALS USED IN PER WAVE ENERGY CONVERTER AND PER WAVE POWER PLANT**

| Material | Weight per WEC [kg] | Weight per WPP [tonnes] |
|---|---|---|
| Concrete | 50200 | 50400 |
| Steel | 12600 | 13100 |
| Cast iron | 1800 | 1800 |
| Stainless steel | 244 | 245 |
| Copper | 189 | 240 |
| NdFeB-magnets | 180 | 180 |
| Plastics and rubber | 166 | 218 |
| Paint | 75 | 76 |
| Zinc | 40 | 44 |
| Aluminium | 17 | 40 |
| Transformer oil, lubrication oil, other chemicals | 8 | 22 |
| Sum | 65519 | 66365 |

Figure 9 is a SimaPro network visualization of the processes needed to produce 1 kWh of wave power electricity delivered to the grid. In this case, the relative contribution to the use of non-renewable energy is shown for each process, with a cut-off rate of 6% for showing processes in the network (no cut-off rate is applied for including processes in the calculations).

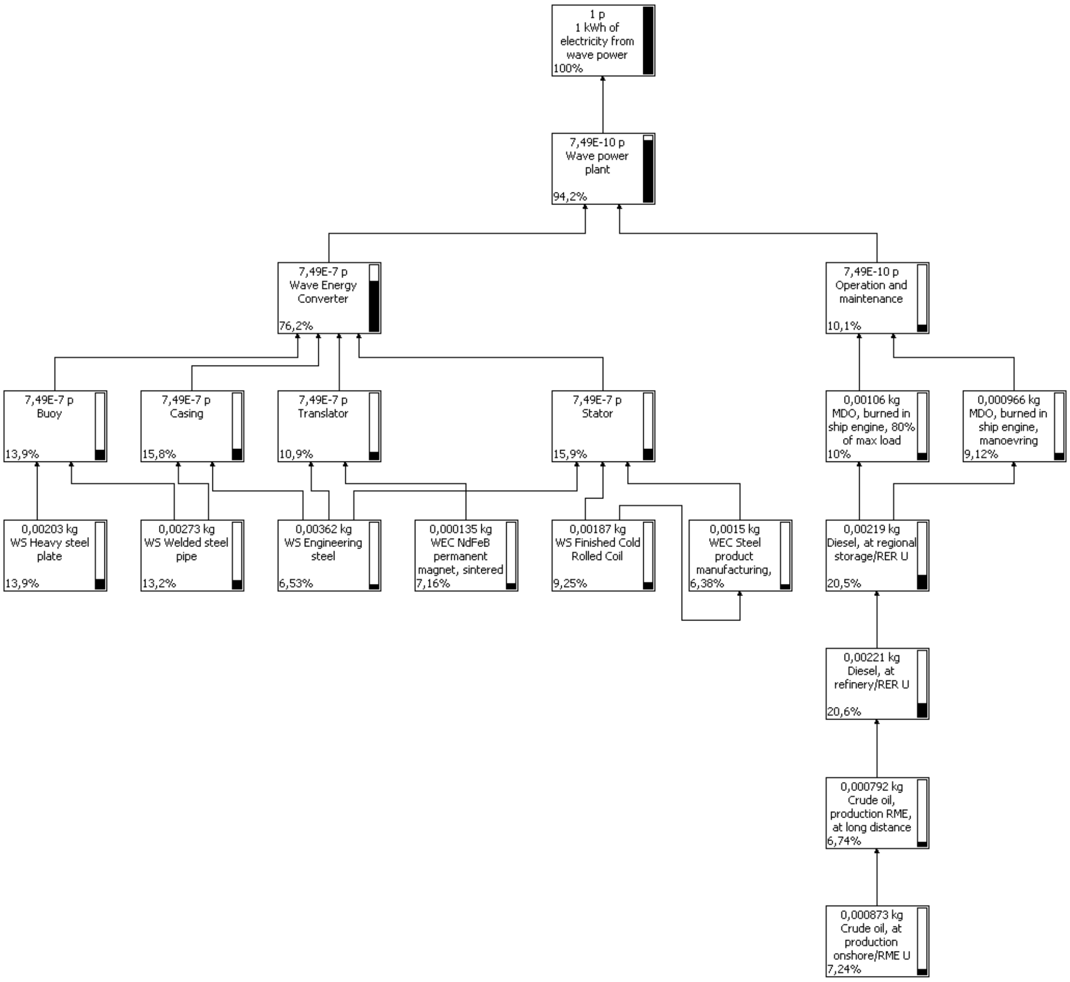



**FIGURE 9: NETWORK DESCRIBING THE PROCESSES NEEDED TO PRODUCE 1 KWH OF ELECTRICITY DELIVERED TO THE GRID. THE CONTRIBUTIONS OF THE VARIOUS PROCESSES TO THE USE OF NON-RENEWABLE ENERGY IS SHOWN (AS PERCENTAGES IN THE LOWER LEFT CORNER AND AS GRAPHIC BARS TO THE RIGHT IN EACH BOX. PROCESSES CONTRIBUTING TO 6% OR MORE TO THE IMPACT CATEGORY ARE SHOWN.**

The results of the calculations are lists containing more than 800 input and output flows. Main input flows (exceeding 0,1 grams in Case SE for flows listed by mass) are presented in table 8. Primary energy carriers are in some cases listed by energy content and in some cases by mass. In table 8 all primary energy carriers are listed by energy content (using the characterization factors in appendix 3). Emissions contributing to the environmental impact categories and outputs to technosphere (materials for recycling and wastes not tracked to the grave) are listed in tables 9 and 10 respectively. Full inventory tables are presented in appendix 2.

**TABLE 9: CALCULATED INPUT OF MATERIALS AND ENERGY RESOURCES PER KWH OF ELECTRICITY DELIVERED TO THE GRID. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.**

| Input | Unit | Amount per kWh delivered to grid [g] | |
|---|---|---|---|
| | | Case NO | Case SE |
| **Material resources** | | | |
| ***Renewable*** | | | |
| Air | g | 3,05 | 10,3 |
| Carbon dioxide, in air | g | 0,32 | 1,06 |
| Oxygen, in air | g | 0,03 | 0,10 |
| *Water* | m3 | 0,06 | 0,22 |
| ***Non-renewable*** | | | |
| Bauxite | g | 0,14 | 0,47 |
| Calcite | g | 3,01 | 10,2 |
| Cerium, 24% in bastnasite, 2.4% in crude ore | g | 0,03 | 0,10 |
| Chromium ore, in ground | g | 0,04 | 0,13 |
| Clay, unspecified | g | 1,10 | 3,70 |
| Copper ore | g | 7,94 | 26,8 |
| Dolomite | g | 0,24 | 0,82 |
| Gravel | g | 31,3 | 106 |
| Inert rock | g | 0,49 | 1,65 |
| *Iron, in ground* | g | 14,1 | 47,5 |
| Limestone | g | 0,88 | 2,98 |
| Sodium chloride, in ground | g | 0,33 | 1,10 |
| *Zinc* | g | 0,09 | 0,30 |
| ***Recycled materials*** | | | |
| Iron scrap | g | 5,07 | 17,1 |
| **Energy** | | | |
| ***Renewable*** | | | |
| Energy, from wood | MJ | 6,69E-05 | 2,26E-04 |
| Energy, geothermal | MJ | 1,38E-06 | 4,65E-06 |
| Energy, gross calorific value, in biomass | MJ | 3,51E-03 | 1,18E-02 |
| Energy, gross calorific value, in biomass, primary forest | MJ | 1,06E-05 | 3,58E-05 |
| Energy, kinetic (in wind) | MJ | 2,66E-04 | 8,73E-04 |
| Energy, solar | MJ | 2,00E-05 | 6,70E-05 |
| Energy, potential (in hydropower reservoir) | MJ | 9,12E-03 | 3,06E-02 |
| Energy, renewable, unspecified | MJ | 8,93E-03 | 3,01E-02 |
| **Sum** | MJ | **0,02** | **0,07** |
| ***Non-renewable*** | | | |
| *Energy from coal* | MJ | 0,23 | 0,78 |
| *Energy from natural gas* | MJ | 0,07 | 0,22 |
| *Energy from oil* | MJ | 0,17 | 0,53 |
| *Energy from uranium* | MJ | 0,03 | 0,09 |
| Energy, non-renewable, unspecified | MJ | 0,01 | 0,05 |
| **Sum** | MJ | **0,52** | **1,69** |

**TABLE 10: CALCULATED EMISSIONS CONTRIBUTING TO IMPACT CATEGORIES. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.**

| Emissions contributing to impact categories | Amount per kWh delivered to grid [g] Case NO | Case SE |
|---|---|---|
| ***Emissions to air*** | | |
| *Carbon dioxide* | 37,1 | 122,8 |
| *Methane* | 0,028 | 0,091 |
| *Halogenated hydrocarbons* | 1,36E-04 | 4,56E-04 |
| *NOx (as NO2)* | 0,119 | 0,362 |
| *Sox (as SO2)* | 0,087 | 0,284 |
| *Aromatic hydrocarbons* | 1,55E-04 | 5,06E-04 |
| *Alcohols* | 6,97E-05 | 2,32E-04 |
| *Aldehydes* | 7,19E-05 | 2,34E-04 |
| *Alkanes (except methane)* | 8,91E-04 | 2,81E-03 |
| *Ammonium salts* | 3,64E-09 | 1,22E-08 |
| Acetic acid | 1,14E-04 | 3,79E-04 |
| Acetone | 4,73E-05 | 1,59E-04 |
| Ammonia | 0,005 | 0,017 |
| Ammonium, ion | 5,34E-13 | 1,80E-12 |
| Chloroform | 1,72E-09 | 5,63E-09 |
| Dinitrogen monoxide | 1,68E-03 | 5,17E-03 |
| Ethene | 3,34E-05 | 1,03E-04 |
| Ethyl acetate | 1,84E-04 | 6,03E-04 |
| Ethyne | 5,70E-07 | 1,91E-06 |
| Formic acid | 6,93E-07 | 2,32E-06 |
| Hydrocarbons, unspecified | 4,32E-04 | 1,46E-03 |
| Isoprene | 9,12E-09 | 3,02E-08 |
| Methyl ethyl ketone | 1,84E-04 | 6,04E-04 |
| Methyl formate | 1,80E-12 | 6,03E-12 |
| Nitrate | 1,46E-08 | 4,83E-08 |
| Nitric oxide | 1,70E-09 | 5,74E-09 |
| NMVOC, non-methane volatile organic compounds | 0,011 | 0,030 |
| Phosphorus | 2,48E-06 | 8,39E-06 |
| Propene | 2,78E-05 | 8,41E-05 |
| Propionic acid | 3,39E-07 | 1,11E-06 |
| Sulfur hexafluoride | 2,80E-07 | 9,28E-07 |
| t-Butyl methyl ether | 2,72E-09 | 9,16E-09 |
| | | |
| ***Emissions to water*** | | |
| Ammonia | 1,98E-08 | 6,68E-08 |
| Ammonium, ion | 0,001 | 0,003 |
| COD, Chemical Oxygen Demand | 0,088 | 0,251 |
| Nitrate | 0,005 | 0,017 |
| Nitrite | 5,00E-05 | 1,69E-04 |
| *Nitrogen* | 0,003 | 0,010 |
| Phosphate | 0,001 | 0,003 |
| *Phosphorus* | 4,20E-05 | 1,41E-04 |
| | | |
| ***Emissions to soil*** | | |
| Ammonia | 2,47E-06 | 8,32E-06 |
| Phosphorus | 4,04E-06 | 1,37E-05 |

**TABELL 11: OUTPUT TO TECHNOSPHERE. LINES IN ITALIC REPRESENT AGGREGATED FLOWS.**

| Output to technosphere | Amount per kWh delivered to grid [g] | |
|---|---|---|
| | Case NO | Case SE |
| **Waste** | | |
| *Nuclear waste* | 4,37E-04 | 1,48E-03 |
| Waste water | 2,11E-14 | 7,11E-14 |
| *Other waste* | 16,6 | 56,1 |
| | | |
| **Materials for recycling** | | |
| Steel | 11,58 | 39,06 |
| Copper | 0,18 | 0,60 |
| Concrete | 38 | 127 |
| Aluminium | 0,03 | 0,10 |

## 6.2 Environmental Impact Assessment

The potential environmental impacts, energy and water use resulting from the SimaPro calculations are presented in tables 11 and 12. The most conspicuous result is the long energy payback time in the Swedish case. The energy payback time is the time needed for the wave power plant to produce the amount of energy that was used to construct it. Considering that the lifetime of the plant is assumed to be twenty years, it is obvious that future generator designs need to be slimmed down considerably to be viable.

The 95% confidence intervals are based on Monte Carlo analysis and reflect uncertainties in background data and transportation distances. No uncertainty is assumed to be associated with the material composition of the plant or the amount of electricity produced. The variation due to these factors are roughly reflected by the varying results for the different power absorption rates presented in tables 11 and 12. The results used for contribution- and sensitivity analysis are marked with light grey.

**TABLE 12: POTENTIAL ENVIRONMENTAL IMPACT, ENERGY AND WATER USE AND ENERGY PAYBACK TIME AT DIFFERENT POWER ABSORPTION RATES, CASE NO. *WATER USE DOES NOT INCLUDE WATER THROUGH TURBINES IN HYDROPOWER PLANTS. **THE UNCERTAINTY OF THE ENERGY PAYBACK TIME IS APPROXIMATED BY THE WEIGHTED MEAN OF THE UNCERTAINTIES FOR RENEWABLE AND NON-RENEWABLE ENERGY.**

| Case NO<br>Absorption [%] | 10 | 12,5 | 15 | 95% confidence interval |
|---|---|---|---|---|
| GWP [kg CO2 eq/kWh] | 0,048 | 0,039 | 0,032 | ± 5% |
| ODP [kg CFC-11 eq/kWh] | 1,85E-09 | 1,48E-09 | 1,23E-09 | ± 48% |
| eq/kWh] | 1,85E-05 | 1,48E-05 | 1,23E-05 | ± 15% |
| Acidification [kg SO2 eq/kWh] | 1,99E-04 | 1,60E-04 | 1,33E-04 | ± 11% |
| Eutrophication [kg PO4 eq/kWh] | 2,93E-05 | 2,34E-05 | 1,95E-05 | ± 19% |
| Non renewable energy [MJ/kWh] | 0,645 | 0,516 | 4,30E-01 | ± 7% |
| Renewable energy [MJ/kWh] | 0,027 | 0,021 | 1,78E-02 | ± 17% |
| Water use [m3/kWh] | 7,08E-04 | 5,67E-04 | 4,72E-04 | ± 7% |
| | | | | |
| Total energy delivered [kWh] | 1,07E+09 | 1,33E+09 | 1,60E+09 | - |
| Energy payback time [years] | 3,7 | 3,0 | 2,5 | ± 7% |

**TABLE 13: POTENTIAL ENVIRONMENTAL IMPACT, ENERGY AND WATER USE AND ENERGY PAYBACK TIME AT DIFFERENT POWER ABSORPTION RATES, CASE SE. *WATER USE DOES NOT INCLUDE WATER THROUGH TURBINES IN HYDROPOWER PLANTS. **THE UNCERTAINTY OF THE ENERGY PAYBACK TIME IS APPROXIMATED BY THE WEIGHTED MEAN OF THE UNCERTAINTIES FOR RENEWABLE AND NON-RENEWABLE ENERGY.**

| Case SE<br>Absorption [%] | 12,5 | 15 | 17,5 | 95% confidence interval |
|---|---|---|---|---|
| GWP [kg CO2 eq/kWh] | 0,152 | 0,126 | 0,108 | ± 5% |
| ODP [kg CFC-11 eq/kWh] | 5,50E-09 | 4,58E-09 | 3,93E-09 | ± 50% |
| eq/kWh] | 5,64E-05 | 4,70E-05 | 4,03E-05 | ± 15% |
| eq/kWh] | 5,97E-04 | 4,97E-04 | 4,26E-04 | ± 12% |
| Eutrophication [kg PO4 eq/kWh] | 8,45E-05 | 7,04E-05 | 6,03E-05 | ± 19% |
| Non renewable energy [MJ/kWh] | 2,028 | 1,690 | 1,45E+00 | ± 8% |
| Renewable energy [MJ/kWh] | 0,087 | 0,072 | 6,19E-02 | ± 16% |
| Water use [m3/kWh] | 2,28E-03 | 1,90E-03 | 1,63E-03 | ± 7% |
| | | | | |
| Total energy delivered [kWh] | 3,28E+08 | 3,95E+08 | 4,63E+08 | - |
| Energy payback time [years] | 11,7 | 9,8 | 8,4 | ± 8% |

# 7 INTERPRETATION

## 7.1 CONTRIBUTION ANALYSIS

Figure 10 shows the relative contribution from different product stages to the impact categories. It is clear that the construction of the wave power plant is the most important production stage, with a relative contribution ranging from 63 to 99% of the potential environmental impact and resource use. The deployment, operation and maintenance and end-of-life phase are dominated by ship operations. The total contribution from these phases ranges from less than one to over forty percent.

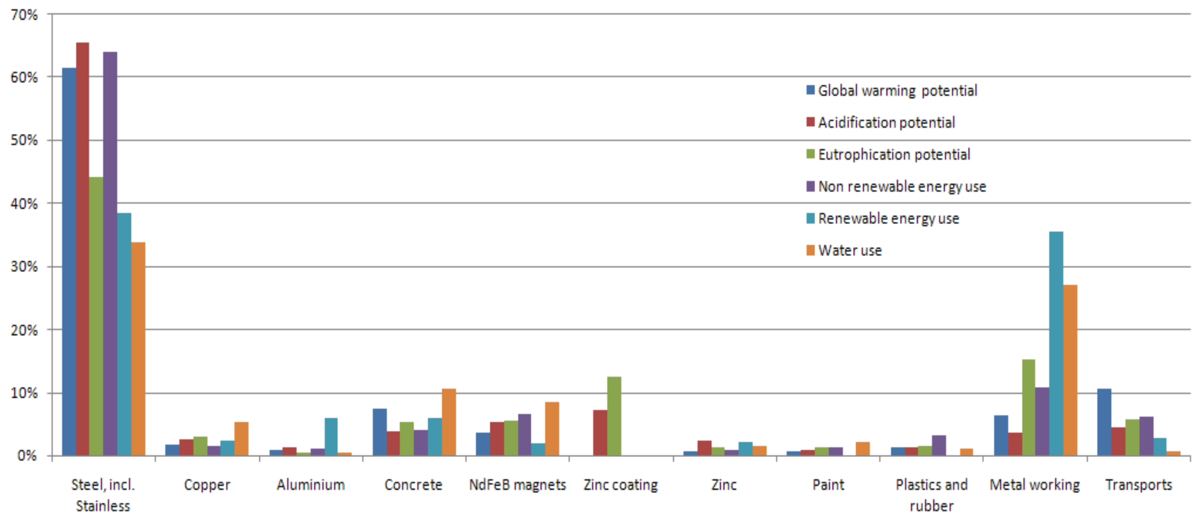

**FIGUR 10. RELATIVE CONTRIBUTION OF DIFFERENT PRODUCT STAGES TO THE ENVIRONMENTAL IMPACT CATEGORIES**

The WPP construction stage is further broken down into different processes in figure 11. Only six impact categories are presented in the figure. The reason for this is that the inventory data for steel does not include emissions of ozone depleting gases or gases contributing to the forming of ground level ozone. With this in mind it is probable that the results for these impact categories are underestimated. The lacking data for some impact categories in some datasets will of course also have an impact on the results presented in figure 10 above. Input data quality is further discussed in chapter 7.3.

It is obvious that the production of steel is the single most important factor. Metal working processes also have a relatively large impact. The large contributions to renewable energy use and water use from metal working processes consist mainly of hydropower and water used in ancillary processes respectively.

The relative contribution from concrete and neodymium-iron-boron-magnets is of about the same magnitude, though 50 tons of concrete and only 180 kg magnets is used for each WEC. The environmental impact from the magnets stems mainly from the production of neodymium oxide, though only about 25% of the magnets consists of neodymium.

The transports presented in figure 10 do not include transports associated with the production of raw materials and semi-finished products. In other words, transports represented by the black arrow in figure 7 (chapter 5) are included in the bars for material production.




**FIGUR 11: PROCESS CONTRIBUTION TO POTENTIAL ENVIRONMENTAL IMPACT AND RESOURCE CONSUMPTION FOR THE CONSTRUCTION OF THE WPP. THE PROCESSES SHOWN REPRESENT 88-98% OF THE ENVIRONMENTAL IMPACT.**

## 7.2 Sensitivity Analysis

The impacts of the following assumptions were assessed in a sensitivity analysis:

- **The weight of the concrete foundation for the WECs** was assumed to be 50 tons. The weight of the foundations is an issue which is not quite settled and could vary as much as 25 tons in each direction. The weight of the foundation constitutes a large part of the WEC weight and will affect transportation and waste treatment needs besides the production of the concrete itself.

- **All metals and all concrete were assumed to be recycled** at the end of the WPP life cycle. The impacts of this assumption was assessed by creating an alternative waste treatment scenario, where all materials were sent to incineration or landfill.

- **The average time needed for maintenance work** was assumed to be two hours per WEC. In the sensitivity analysis the impact was investigated of doubling the maintenance time.

- **The distance from the production site in Lysekil to the WPP site** was assumed to be 650 km in the Norwegian case. In the sensitivity analysis this distance was adjusted by 250 km in both directions, the relative change in environmental impact representing a distance span from 400-900 km.

- **The approximation of cold forming and cutting of steel** by cold rolling and "steel product manufacturing" might, based on the contribution analysis, have a significant impact on the final results. By adjusting the environmental impact stemming from these processes by 50% it is assumed that a "worst case scenario" is modelled regarding the importance of these approximations.

The results of the sensitivity analysis are presented in table 13. The sensitivity analysis was carried out for both the Norwegian and the Swedish case, except regarding the distance to the production site. Since the results were very similar for both cases only the results for case NO is presented. Most of the relative changes in environmental impacts are well within the 95% confidence intervals presented in tables 11 and 12 (chapter 6). The impact of not recycling the wave power plant at the end of its life cycle is very small for most impact categories. Expanding the system boundaries would however increase the importance of recycling, since the recycled materials will replace virgin materials in subsequent life cycles. This is not reflected in the present study. The increased environmental impact of the alternative waste scenario consists of emissions and resource use associated with waste incineration and landfills.

The approximations made regarding cold forming of steel pressure vessel heads and cutting of stator sheet might, as can be seen in table 13, have a rather large impact on the final results concerning energy and water use.

**TABLE 14: RESULTS OF THE SENSITIVITY ANALYSIS**

| Relative change | Case NO ±25 t concrete | Case NO No recycling | Case NO 4 h maintenance | Case NO ±250 km dist to Lysekil | Case NO ±50% impact from cold forming and cutting of steel |
|---|---|---|---|---|---|
| GWP | ±3% | 0% | 3% | ±1% | ±3% |
| ODP | -3% | 1% | 9% | ±3% | ±5% |
| Photochemical oxidation | ±4% | 5% | 7% | ±3% | ±2% |
| Acidification | ±2% | 2% | 7% | ±3% | ±1% |
| Eutrophication | ±3% | 4% | 8% | ±4% | ±2% |
| Non renewable energy | ±2% | 0% | 3% | ±1% | ±4% |
| Renewable energy | ±3% | 1% | 0% | 0% | ±13% |
| Energy, total | ±2% | 0% | 3% | ±1% | ±5% |
| Water use | ±5% | 2% | 1% | 0% | ±8% |

## 7.3 Consistency Check

### *7.3.1 Geographical, Temporal and Technological Coverage*

The background data used in the study in many cases reflect average European conditions. This is not a problem regarding materials such as e.g. steel and copper since these products are traded across national (and regional) boarders. Concrete is a material that is not traded across long distances. The Ecoinvent data set for concrete reflects Swiss production and has been modified by using the Swedish electricity mix instead of the Swiss. The same was done regarding production processes taking place in Sweden, for which only datasets reflecting average European conditions were available. The overall assessment is that no major problems regarding geographical coverage are associated with the LCA results.

All background data sources do not fulfill the requirement of not being more than ten years old. However, the relative contribution of these data (concerning some plastics and parts of the NTM transport dataset) is estimated to be well below 1%, based on the contribution analysis.

The approximations regarding manufacturing processes described in chapter 5.1.6 also have an impact on the results. This impact is estimated to be negligible, with the possible exception of the approximations regarding cold forming of steel and cutting of stator sheet, which were assessed in the sensitivity analysis. These approximations are however considered to be the best that could be done with available data. In conclusion, the technology coverage is judged to be adequate in relation to the goal and scope of the study.

### *7.3.2 Data quality*

Generic data was collected from selected sources with a few exceptions. Based on the contribution analysis, data from "other generic sources" are not estimated to contribute to more than a few percents of the final results. Thus the study well complies with the GPI requirement that less than 10% of the environmental impact should stem from "other generic data".

There are a few issues regarding the selected generic data sources which probably affect the LCA results. The most important of these is the fact that the Worldsteel data does not include ozone depleting gases (OPD) or gases contributing to the formation of ground-level ozone (photochemical oxidation). Some of the latter substances are nevertheless included in the data, since they also contribute to other impact categories. Emissions of ODP-gases from the WPP life cycle mainly stem from the production of crude oil. Steel production constitutes about 20% of the total crude oil used in the WPP life cycle, roughly indicating that 20% of ODP-gases are unaccounted for in the study. However, the data used in the study are a few years old, and the use of ozone depleting substances has decreased steadily in the last decade, suggesting that the emissions of these substances are overestimated in the study. The conclusion is simply that the results for these two categories are hefted with large uncertainties.

The steel data also contains some waste flows not followed to the grave, constituting most of the waste flows listed in table 10. Some untreated waste flows also stem from the data for aluminium, but these waste flows are very small compared to those associated with steel production. Treatment of this waste is not included in the study, meaning an underestimation of the environmental impact. This effect is however expected to be very small, considering that waste treatment processes constitute a very small part of the final results ant that the steel production waste consists mainly of inert mining waste (rock) (14).

## 7.4 Completeness Check

Of the total weight of the WPP more than 99,9% is estimated to be included in the study, including all materials associated with large environmental impact per unit mass. The manufacturing of marine substations is not included in the study. The "amounts" of manufacturing processes is proportional to the amounts of materials used. Considering that the substations constitute less than 0,5% of the materials used in the WPP it is not likely that the exclusion of marine substation manufacturing processes will affect the final results by more than about 0,1%. The importance of other processes that were neglected, such as painting of steel parts, assembling of components and use of e.g. lubricant oil in ship engines, are also estimated to be of the negligible magnitude. The Ecoinvent database is known to be conservative in its assumptions and environmental impact stemming from Ecoinvent data is thus not assumed to be underestimated.

The overall assessment is that the study complies to the 1% cut-off rule regarding mass flows as well as potential environmental impact and resource use.

# 8 CONCLUSIONS AND OUTLOOK

As with non-fuel based electricity production in general, the environmental impact of wave power stems mainly from the plant construction phase. Thus, the amounts of materials used in the construction of the wave power plant are of great importance for the plants´ environmental performance.  Wave power at the present stage of development uses relatively large amounts of materials per kWh of produced electricity. In particular, steel production contributes to a large part of the environmental impact, ranging from about thirty to almost sixty percent of the results for the various impact categories. New designs of wave energy converters for serial production are estimated to reduce the amounts of steel by as much as fifty percent, indicating that the environmental performance of this wave power concept can be improved significantly.

Though concrete constitutes about 75% of the materials used in the wave power plant, the relative contribution of concrete to the overall results is at most about ten percent. Reducing the amounts of concrete used may be important from an economical point of view, but is not as important an environmental factor. It is also worth noting that the production of neodymium-iron-boron permanent magnets contributes to almost as much of the potential environmental impact as the production of concrete, though the magnets make up less than 0,3% of the total weight of used materials.

The sensitivity analysis indicated that recycling of used material at the end of the WPP life cycle does not decrease the environmental impact of the system significantly. Of course, in a wider perspective this is not true. The recycled materials will substitute virgin materials in subsequent products, reducing the energy use and environmental impact of their life cycles. This is a weakness of the modular approach to LCA used in the present study.

Though most of the potential environmental impacts stem from material use, the deployment, maintenance and disassembly phases are not of negligible importance. The environmental impact of these phases could be decreased significantly e.g. by transporting the wave energy converters by train, using biofuel for the ships and decreasing the time needed for work out at sea.

The present life cycle assessment was performed for a hypothetical wave power plant, involving many assumptions and estimations. In the future, LCA studies of existing plants will provide more reliable results. Also, as wave power technology matures, LCA studies will produce results that are comparable to those for other energy conversion technologies. This is the most obvious possible improvement of the study.  Other possibilities include the improvement of background data, by e.g. collecting data from specific sites of component and material production, which was not practicable within the time frame of this master´s degree project. Improvement of generic databases will of course also increase the reliability of this type of study.

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# Appendix 1: Description of Background Data Sources

**TABLE A11: DESCRIPTION OF BACKGROUND DATA SOURCES**

| Source | Reference year | Geographical coverage | Production coverage | Allocation methods |
|---|---|---|---|---|
| **EAA, European Aluminium Association** | 2005 | EU 27 + EFTA average | ≥ 90% of primary Al production, 33% of extrusion output | Mass / system expansion |
| **Deutsches Kupfer-institut** | 2000 | EU 25 average | > 95% of | Market value/ system expansion |
| **Worldsteel** | 2005 | EU 15 average | 60% of | Market value/ net calorific value/ system expansion |
| **World stainless** | 2005 | European average | Unknown | Market value/ net calorific value/ system expansion |
| **PlasticsEurope** | 1996-1999 | European average | Unknown | Element content /mass / system expansion |
| **NTM, Nätverket för trafik och miljön** | 1997-1999 | Swedish average | Unknown / not applicable | Unknown |
| **Cooper, Gustavsson (emissions from combustion of ship fuels)** | 2002 | Swedish average | (Measurements from 62 ships, > 180 engines) | No allocation |
| **CPM LCA database (cleaning and sand blastering of cast iron)** | 2002 | SKF Mekan AB, Katrineholm, Sweden | Site specific | Mass |
| **Ecoinvent** | 2000-2005 (with exceptions) | Varying | Varying | Physical and economic causal relationships |

# APPENDIX 2: INVENTORY TABLES

**TABLE A21: INPUT OF NATURAL RESOURCES PER KWH OF PRODUCED ELECTRICITY FROM WAVE POWER**

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Air | kg | 0,0037062 | 0,0125074 |
| Aluminium, 24% in bauxite, 11% in crude ore, in ground | kg | 1,768E-06 | 5,964E-06 |
| Anhydrite, in ground | kg | 2,264E-09 | 7,636E-09 |
| Barite, 15% in crude ore, in ground | kg | 5,194E-07 | 1,752E-06 |
| Barium sulphate | kg | 3,275E-18 | 1,105E-17 |
| Basalt, in ground | kg | 2,503E-07 | 8,448E-07 |
| Bauxite, in ground | kg | 0,0001405 | 0,000474 |
| Borax, in ground | kg | 9,038E-11 | 3,048E-10 |
| Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground | kg | 2,123E-08 | 7,166E-08 |
| Calcite, in ground | kg | 0,0030119 | 0,0101635 |
| Calcium chloride | kg | 3,334E-16 | 1,125E-15 |
| Carbon dioxide, in air | kg | 0,0003044 | 0,0010258 |
| Carbon, in organic matter, in soil | kg | 1,531E-07 | 5,166E-07 |
| Cerium, 24% in bastnasite, 2.4% in crude ore, in ground | kg | 3,004E-05 | 0,0001014 |
| Chromium ore, in ground | kg | 3,87E-05 | 0,0001306 |
| Chromium, 25.5% in chromite, 11.6% in crude ore, in ground | kg | 1,91E-07 | 6,442E-07 |
| Chrysotile, in ground | kg | 5,534E-09 | 1,867E-08 |
| Cinnabar, in ground | kg | 5,433E-10 | 1,833E-09 |
| Clay, bentonite, in ground | kg | 3,86E-07 | 1,299E-06 |
| Clay, unspecified, in ground | kg | 0,0010952 | 0,003696 |
| Coal, brown (lignite) | kg | 3,855E-05 | 0,0001301 |
| Coal, brown, in ground | kg | 0,0004779 | 0,001594 |
| Coal, hard, unspecified, in ground | kg | 0,0072943 | 0,0246058 |
| Cobalt, in ground | kg | 8,257E-11 | 2,475E-10 |
| Colemanite ore | kg | 8,498E-11 | 2,868E-10 |
| Colemanite, in ground | kg | 4,545E-06 | 1,534E-05 |
| Copper ore, in ground | kg | 0,0079445 | 0,02681 |
| Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground | kg | 3,508E-09 | 1,183E-08 |
| Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground | kg | 3,913E-09 | 1,319E-08 |
| Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground | kg | 1,038E-09 | 3,499E-09 |
| Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground | kg | 2,768E-08 | 9,339E-08 |
| Diatomite, in ground | kg | 1,883E-14 | 6,329E-14 |
| Dolomite, in ground | kg | 0,0002435 | 0,0008217 |
| Energy, from coal | MJ | 0,0014696 | 0,0049594 |
| Energy, from coal, brown | MJ | 0,0011495 | 0,0038791 |
| Energy, from gas, natural | MJ | 0,0022582 | 0,0076207 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Energy, from oil | MJ | 0,0077287 | 0,026082 |
| Energy, from uranium | MJ | 0,0010164 | 0,0034301 |
| Energy, from wood | MJ | 6,686E-05 | 0,0002256 |
| Energy, geothermal | MJ | 1,378E-06 | 4,65E-06 |
| Energy, gross calorific value, in biomass | MJ | 0,0033754 | 0,011378 |
| Energy, gross calorific value, in biomass, primary forest | MJ | 1,062E-05 | 3,581E-05 |
| Energy, kinetic (in wind), converted | MJ | 0,0002971 | 0,0009947 |
| Energy, non-renewable, unspecified | MJ | 0,0134056 | 0,0452398 |
| Energy, potential (in hydropower reservoir), converted | MJ | 0,0087864 | 0,0296044 |
| Energy, renewable | MJ | 0,0089333 | 0,030147 |
| Energy, solar | MJ | 1,732E-05 | 5,845E-05 |
| Energy, solar, converted | MJ | 3,442E-06 | 1,151E-05 |
| Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground | kg | 7,527E-08 | 2,54E-07 |
| Feldspar, in ground | kg | 3,789E-09 | 1,279E-08 |
| Ferromanganese | kg | 1,59E-20 | 5,367E-20 |
| Fluorine, 4.5% in apatite, 1% in crude ore, in ground | kg | 4,786E-09 | 1,558E-08 |
| Fluorine, 4.5% in apatite, 3% in crude ore, in ground | kg | 3,373E-09 | 1,113E-08 |
| Fluorspar, 92%, in ground | kg | 2,45E-07 | 8,098E-07 |
| Fluorspar, in ground | kg | 1,015E-06 | 3,425E-06 |
| Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground | kg | 1,879E-07 | 6,339E-07 |
| Gallium, 0.014% in bauxite, in ground | kg | 1,248E-18 | 4,083E-18 |
| Gas, mine, off-gas, process, coal mining/m3 | m3 | 6,167E-06 | 2,071E-05 |
| Gas, natural (0,8 kg/m3) | m3 | 0,0009137 | 0,0030834 |
| Gas, natural, in ground | m3 | 0,0009453 | 0,0031354 |
| Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground | kg | 1,453E-12 | 4,903E-12 |
| Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground | kg | 2,664E-12 | 8,99E-12 |
| Gold, Au 1.4E-4%, in ore, in ground | kg | 3,19E-12 | 1,076E-11 |
| Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground | kg | 4,872E-12 | 1,644E-11 |
| Gold, Au 4.3E-4%, in ore, in ground | kg | 1,208E-12 | 4,075E-12 |
| Gold, Au 4.9E-5%, in ore, in ground | kg | 2,892E-12 | 9,76E-12 |
| Gold, Au 6.7E-4%, in ore, in ground | kg | 4,478E-12 | 1,511E-11 |
| Gold, Au 7.1E-4%, in ore, in ground | kg | 5,049E-12 | 1,704E-11 |
| Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground | kg | 3,025E-13 | 1,021E-12 |
| Granite, in ground | kg | 1,136E-11 | 3,835E-11 |
| Gravel, in ground | kg | 0,0313315 | 0,1057337 |
| Gypsum, in ground | kg | 3,921E-08 | 1,323E-07 |
| Heavy spar (barytes) | kg | 2,467E-07 | 8,325E-07 |
| Helium, 0.08% in natural gas, in ground | kg | 6,303E-18 | 2,061E-17 |
| Ilmenite, in ground | kg | 1,511E-10 | 5,098E-10 |
| Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground | kg | 3,537E-10 | 1,194E-09 |
| Inert rock | kg | 0,0004898 | 0,001653 |
| Iron ore, in ground | kg | 7,147E-05 | 0,0002412 |
| Iron, 46% in ore, 25% in crude ore, in ground | kg | 8,195E-05 | 0,0002765 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Iron, in ground | kg | 0,0139453 | 0,0470609 |
| Kaolin ore | kg | 3,423E-11 | 1,155E-10 |
| Kaolinite, 24% in crude ore, in ground | kg | 1,724E-08 | 5,813E-08 |
| Kieserite, 25% in crude ore, in ground | kg | 5,21E-11 | 1,757E-10 |
| Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground | kg | 9,007E-06 | 3,039E-05 |
| Lead - zink ore (4,6%-0,6%) | kg | 2,03E-08 | 6,851E-08 |
| Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground | kg | 6,303E-07 | 2,127E-06 |
| Lead, in ground | kg | 3,187E-20 | 1,075E-19 |
| Limestone, in ground | kg | 0,0008835 | 0,0029816 |
| Magnesite, 60% in crude ore, in ground | kg | 1,023E-06 | 3,451E-06 |
| Magnesium chloride leach (40%) | kg | 3,187E-08 | 1,075E-07 |
| Magnesium, 0.13% in water | kg | 3,992E-12 | 1,347E-11 |
| Manganese ore, in ground | kg | 4,434E-06 | 1,496E-05 |
| Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground | kg | 2,359E-08 | 7,96E-08 |
| Metamorphous rock, graphite containing, in ground | kg | 1,493E-09 | 5,036E-09 |
| Molybdenite (Mo 0,24%) | kg | 6,905E-09 | 2,33E-08 |
| Molybdenum ore, in ground | kg | 6,699E-06 | 2,261E-05 |
| Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground | kg | 5,144E-10 | 1,736E-09 |
| Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground | kg | 1,364E-11 | 4,597E-11 |
| Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground | kg | 8,464E-09 | 2,854E-08 |
| Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground | kg | 4,996E-11 | 1,684E-10 |
| Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground | kg | 1,707E-08 | 5,757E-08 |
| Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground | kg | 4,954E-06 | 1,672E-05 |
| Nickel ore, in ground | kg | 2,221E-05 | 7,495E-05 |
| Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground | kg | 8,084E-09 | 2,725E-08 |
| Nickel, 1.98% in silicates, 1.04% in crude ore, in ground | kg | 2,076E-07 | 7,002E-07 |
| Nitrogen, in air | kg | 6,917E-11 | 2,334E-10 |
| Occupation, arable, non-irrigated | m2a | 1,38E-06 | 4,658E-06 |
| Occupation, construction site | m2a | 1,794E-07 | 6,029E-07 |
| Occupation, dump site | m2a | 9,398E-06 | 3,166E-05 |
| Occupation, dump site, benthos | m2a | 5,808E-11 | 1,911E-10 |
| Occupation, forest, intensive | m2a | 2,785E-06 | 9,395E-06 |
| Occupation, forest, intensive, normal | m2a | 6,73E-05 | 0,0002269 |
| Occupation, forest, intensive, short-cycle | m2a | 2,663E-06 | 8,984E-06 |
| Occupation, industrial area | m2a | 7,829E-07 | 2,595E-06 |
| Occupation, industrial area, benthos | m2a | 5,321E-13 | 1,751E-12 |
| Occupation, industrial area, built up | m2a | 1,312E-08 | 4,423E-08 |
| Occupation, industrial area, vegetation | m2a | 6,777E-09 | 2,285E-08 |
| Occupation, mineral extraction site | m2a | 8,92E-05 | 0,000301 |
| Occupation, permanent crop, fruit, intensive | m2a | 5,17E-06 | 1,744E-05 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Occupation, shrub land, sclerophyllous | m2a | 2,016E-07 | 6,801E-07 |
| Occupation, traffic area, rail embankment | m2a | 1,795E-10 | 5,807E-10 |
| Occupation, traffic area, rail network | m2a | 1,985E-10 | 6,421E-10 |
| Occupation, traffic area, road embankment | m2a | 7,109E-07 | 2,397E-06 |
| Occupation, traffic area, road network | m2a | 7,005E-10 | 2,297E-09 |
| Occupation, urban, discontinuously built | m2a | 2,676E-14 | 8,751E-14 |
| Occupation, water bodies, artificial | m2a | 3,005E-05 | 0,0001013 |
| Occupation, water courses, artificial | m2a | 5,836E-06 | 1,966E-05 |
| Oil, crude, in ground | kg | 0,0038095 | 0,0116945 |
| Olivine, in ground | kg | 1,217E-09 | 4,104E-09 |
| Oxygen, in air | kg | 3,015E-05 | 0,0001018 |
| Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground | kg | 3,478E-12 | 1,029E-11 |
| Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground | kg | 8,358E-12 | 2,473E-11 |
| Peat, in ground | kg | 2,564E-05 | 8,653E-05 |
| Phosphate ore, in ground | kg | 8,763E-13 | 2,957E-12 |
| Phosphorus minerals | kg | 2,806E-10 | 9,47E-10 |
| Phosphorus pentoxide | kg | 1,001E-17 | 3,379E-17 |
| Phosphorus, 18% in apatite, 12% in crude ore, in ground | kg | 2,731E-08 | 9,117E-08 |
| Phosphorus, 18% in apatite, 4% in crude ore, in ground | kg | 1,914E-08 | 6,232E-08 |
| Potassium chloride | kg | 8,026E-11 | 2,708E-10 |
| Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground | kg | 5,256E-07 | 1,774E-06 |
| Precious metal ore | kg | 3,423E-10 | 1,155E-09 |
| Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground | kg | 7,334E-14 | 2,142E-13 |
| Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground | kg | 2,629E-13 | 7,68E-13 |
| Pumice, in ground | kg | 3,305E-12 | 1,115E-11 |
| Renewable fuels, unspecified | kg | 6,55E-14 | 2,211E-13 |
| Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground | kg | 7,285E-14 | 2,128E-13 |
| Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground | kg | 2,282E-13 | 6,664E-13 |
| Rhenium, in crude ore, in ground | kg | 1,063E-13 | 3,117E-13 |
| Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground | kg | 3,751E-07 | 1,266E-06 |
| Sand, quartz, in ground | kg | 6,924E-06 | 2,337E-05 |
| Sand, unspecified, in ground | kg | 2,243E-07 | 7,57E-07 |
| Shale, in ground | kg | 6,413E-09 | 2,163E-08 |
| Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground | kg | 3,206E-11 | 1,082E-10 |
| Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground | kg | 2,286E-11 | 7,714E-11 |
| Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground | kg | 2,111E-12 | 7,122E-12 |
| Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground | kg | 4,82E-12 | 1,627E-11 |
| Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground | kg | 4,725E-12 | 1,594E-11 |
| Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground | kg | 3,117E-12 | 1,052E-11 |
| Slate, in ground | kg | 2,945E-19 | 9,938E-19 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Sodium chloride, in ground | kg | 0,000326 | 0,0010998 |
| Sodium nitrate, in ground | kg | 1,544E-13 | 5,209E-13 |
| Sodium sulfate | kg | 1,257E-10 | 4,242E-10 |
| Sodium sulphate, various forms, in ground | kg | 2,39E-06 | 8,059E-06 |
| Soil, unspecified, in ground | kg | 1,393E-06 | 4,7E-06 |
| Stibnite, in ground | kg | 1,957E-15 | 6,577E-15 |
| Sulfur, bonded | kg | 2,732E-14 | 9,221E-14 |
| Sulfur, in ground | kg | 2,094E-06 | 7,066E-06 |
| Sylvite, 25 % in sylvinite, in ground | kg | 8,627E-07 | 2,911E-06 |
| Talc, in ground | kg | 3,34E-08 | 1,127E-07 |
| Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground | kg | 2,53E-11 | 8,537E-11 |
| Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground | kg | 3,429E-12 | 1,157E-11 |
| Tin ore, in ground | kg | 2,83E-19 | 9,549E-19 |
| Tin, 79% in cassiterite, 0.1% in crude ore, in ground | kg | 2,776E-09 | 9,37E-09 |
| TiO2, 54% in ilmenite, 2.6% in crude ore, in ground | kg | 1,493E-07 | 4,94E-07 |
| TiO2, 95% in rutile, 0.40% in crude ore, in ground | kg | 2,502E-11 | 8,442E-11 |
| Titanium ore, in ground | kg | 2,148E-09 | 7,249E-09 |
| Transformation, from arable | m2 | 6,576E-10 | 2,218E-09 |
| Transformation, from arable, non-irrigated | m2 | 2,55E-06 | 8,604E-06 |
| Transformation, from arable, non-irrigated, fallow | m2 | 2,095E-10 | 7,066E-10 |
| Transformation, from dump site, inert material landfill | m2 | 1,218E-08 | 4,109E-08 |
| Transformation, from dump site, residual material landfill | m2 | 1,638E-08 | 5,523E-08 |
| Transformation, from dump site, sanitary landfill | m2 | 2,032E-09 | 6,847E-09 |
| Transformation, from dump site, slag compartment | m2 | 9,71E-09 | 3,277E-08 |
| Transformation, from forest | m2 | 1,999E-08 | 6,744E-08 |
| Transformation, from forest, extensive | m2 | 6,259E-07 | 2,111E-06 |
| Transformation, from forest, intensive, clear-cutting | m2 | 9,511E-08 | 3,208E-07 |
| Transformation, from industrial area | m2 | 5,023E-09 | 1,648E-08 |
| Transformation, from industrial area, benthos | m2 | 4,989E-15 | 1,642E-14 |
| Transformation, from industrial area, built up | m2 | 6,823E-12 | 2,221E-11 |
| Transformation, from industrial area, vegetation | m2 | 1,164E-11 | 3,789E-11 |
| Transformation, from mineral extraction site | m2 | 2,62E-06 | 8,839E-06 |
| Transformation, from pasture and meadow | m2 | 7,789E-08 | 2,622E-07 |
| Transformation, from pasture and meadow, intensive | m2 | 2,081E-09 | 7,022E-09 |
| Transformation, from sea and ocean | m2 | 1,986E-10 | 6,652E-10 |
| Transformation, from shrub land, sclerophyllous | m2 | 7,674E-08 | 2,587E-07 |
| Transformation, from tropical rain forest | m2 | 9,511E-08 | 3,208E-07 |
| Transformation, from unknown | m2 | 1,074E-05 | 3,626E-05 |
| Transformation, to arable | m2 | 3,524E-08 | 1,182E-07 |
| Transformation, to arable, non-irrigated | m2 | 2,552E-06 | 8,611E-06 |
| Transformation, to arable, non-irrigated, fallow | m2 | 4,249E-09 | 1,434E-08 |
| Transformation, to dump site | m2 | 6,686E-08 | 2,251E-07 |
| Transformation, to dump site, benthos | m2 | 5,808E-11 | 1,911E-10 |
| Transformation, to dump site, inert material landfill | m2 | 1,218E-08 | 4,109E-08 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Transformation, to dump site, residual material landfill | m2 | 1,638E-08 | 5,523E-08 |
| Transformation, to dump site, sanitary landfill | m2 | 2,032E-09 | 6,847E-09 |
| Transformation, to dump site, slag compartment | m2 | 9,71E-09 | 3,277E-08 |
| Transformation, to forest | m2 | 2,618E-06 | 8,836E-06 |
| Transformation, to forest, intensive | m2 | 1,854E-08 | 6,256E-08 |
| Transformation, to forest, intensive, clear-cutting | m2 | 9,511E-08 | 3,208E-07 |
| Transformation, to forest, intensive, normal | m2 | 5,288E-07 | 1,783E-06 |
| Transformation, to forest, intensive, short-cycle | m2 | 9,511E-08 | 3,208E-07 |
| Transformation, to heterogeneous, agricultural | m2 | 5,103E-12 | 1,676E-11 |
| Transformation, to industrial area | m2 | 8,342E-09 | 2,755E-08 |
| Transformation, to industrial area, benthos | m2 | 1,405E-10 | 4,741E-10 |
| Transformation, to industrial area, built up | m2 | 1,492E-09 | 5,021E-09 |
| Transformation, to industrial area, vegetation | m2 | 7,536E-11 | 2,532E-10 |
| Transformation, to mineral extraction site | m2 | 8,75E-06 | 2,953E-05 |
| Transformation, to pasture and meadow | m2 | 7,951E-11 | 2,598E-10 |
| Transformation, to permanent crop, fruit, intensive | m2 | 7,278E-08 | 2,455E-07 |
| Transformation, to sea and ocean | m2 | 4,989E-15 | 1,642E-14 |
| Transformation, to shrub land, sclerophyllous | m2 | 4,029E-08 | 1,359E-07 |
| Transformation, to traffic area, rail embankment | m2 | 4,177E-13 | 1,351E-12 |
| Transformation, to traffic area, rail network | m2 | 4,591E-13 | 1,485E-12 |
| Transformation, to traffic area, road embankment | m2 | 5,537E-09 | 1,867E-08 |
| Transformation, to traffic area, road network | m2 | 7,818E-12 | 2,564E-11 |
| Transformation, to unknown | m2 | 2,492E-08 | 8,362E-08 |
| Transformation, to urban, discontinuously built | m2 | 5,33E-16 | 1,743E-15 |
| Transformation, to water bodies, artificial | m2 | 1,962E-06 | 6,619E-06 |
| Transformation, to water courses, artificial | m2 | 7,223E-08 | 2,433E-07 |
| Ulexite, in ground | kg | 1,295E-11 | 4,371E-11 |
| Uranium, in ground | kg | 5,907E-08 | 1,986E-07 |
| Water, cooling, unspecified natural origin/kg | kg | 1,166E-06 | 3,933E-06 |
| Water, cooling, unspecified natural origin/m3 | m3 | 0,0001597 | 0,0005326 |
| Water, lake | m3 | 1,64E-05 | 5,535E-05 |
| Water, process and cooling, unspecified natural origin | m3 | 2,516E-05 | 8,492E-05 |
| Water, river | m3 | 6,855E-05 | 0,0002302 |
| Water, salt, ocean | m3 | 4,338E-06 | 1,423E-05 |
| Water, salt, sole | m3 | 2,073E-06 | 6,072E-06 |
| Water, turbine use, unspecified natural origin | m3 | 0,0609409 | 0,2052783 |
| Water, unspecified natural origin/kg | kg | 0,1883521 | 0,6356283 |
| Water, unspecified natural origin/m3 | m3 | 6,403E-05 | 0,000214 |
| Water, well, in ground | m3 | 3,88E-05 | 0,0001309 |
| Vermiculite, in ground | kg | 2,031E-14 | 6,259E-14 |
| Volume occupied, final repository for low-active radioactive waste | m3 | 1,113E-10 | 3,739E-10 |
| Volume occupied, final repository for radioactive waste | m3 | 2,763E-11 | 9,287E-11 |
| Volume occupied, reservoir | m3y | 8,618E-05 | 0,0002899 |
| Volume occupied, underground deposit | m3 | 5,155E-09 | 1,738E-08 |

| Input of natural resources | Unit | Case NO | Case SE |
|---|---|---|---|
| Wood (16.9 MJ/kg) | kg | 1,821E-09 | 6,144E-09 |
| Wood, hard, standing | m3 | 8,521E-08 | 2,872E-07 |
| Wood, primary forest, standing | m3 | 9,848E-10 | 3,322E-09 |
| Wood, soft, standing | m3 | 2,295E-07 | 7,737E-07 |
| Wood, unspecified, standing/m3 | m3 | 1,038E-10 | 3,502E-10 |
| Zinc ore, in ground | kg | 1,065E-08 | 3,595E-08 |
| Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground | kg | 7,491E-05 | 0,0002528 |
| Zinc, in ground | kg | 1,483E-05 | 5,005E-05 |
| Zirconium, 50% in zircon, 0.39% in crude ore, in ground | kg | 3,48E-11 | 1,174E-10 |

**TABLE A22: EMISSIONS TO AIR CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES**

| Emissions to air | Unit | Case NO | Case SE |
|---|---|---|---|
| 1-Propanol | kg | 5,672E-18 | 1,855E-17 |
| 2-Propanol | kg | 1,579E-10 | 5,329E-10 |
| Acetaldehyde | kg | 3,872E-09 | 1,299E-08 |
| Acetic acid | kg | 1,139E-07 | 3,839E-07 |
| Acetone | kg | 4,73E-08 | 1,596E-07 |
| Ammonia | kg | 5,201E-06 | 1,753E-05 |
| Ammonium carbonate | kg | 3,526E-12 | 1,189E-11 |
| Ammonium nitrate | kg | 4,628E-14 | 1,562E-13 |
| Ammonium, ion | kg | 5,341E-16 | 1,802E-15 |
| Benzaldehyde | kg | 8,513E-12 | 2,867E-11 |
| Benzene | kg | 9,165E-08 | 3,02E-07 |
| Benzene, 1,2,4-trimethyl- | kg | 4,81E-16 | 1,623E-15 |
| Benzene, ethyl- | kg | 4,14E-09 | 1,243E-08 |
| Butane | kg | 1,808E-07 | 5,42E-07 |
| Butanol | kg | 5,736E-10 | 1,936E-09 |
| Carbon dioxide | kg | 0,0221362 | 0,0747025 |
| Carbon dioxide, fossil | kg | 0,0156092 | 0,0489074 |
| Carbon dioxide, land transformation | kg | 1,574E-06 | 5,307E-06 |
| Chloroform | kg | 1,711E-12 | 5,759E-12 |
| Cumene | kg | 2,696E-08 | 9,092E-08 |
| Cyclohexane | kg | 3,01E-13 | 1,016E-12 |
| Dinitrogen monoxide | kg | 1,584E-06 | 5,181E-06 |
| Ethane | kg | 1,696E-07 | 5,489E-07 |
| Ethane, 1,1-difluoro-, HFC-152a | kg | 1,621E-16 | 5,302E-16 |
| Ethane, 1,1,1-trichloro-, HCFC-140 | kg | 3,858E-14 | 1,301E-13 |
| Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | kg | 3,155E-12 | 1,061E-11 |
| Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 | kg | 1,939E-14 | 6,543E-14 |
| Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 | kg | 4,877E-11 | 1,64E-10 |
| Ethane, hexafluoro-, HFC-116 | kg | 3,312E-10 | 1,118E-09 |
| Ethanol | kg | 1,277E-09 | 4,24E-09 |
| Ethene | kg | 3,174E-08 | 1,04E-07 |
| Ethene, tetrachloro- | kg | 1,306E-07 | 4,408E-07 |
| Ethyl acetate | kg | 1,842E-07 | 6,215E-07 |
| Ethyne | kg | 5,707E-10 | 1,925E-09 |
| Formaldehyde | kg | 6,677E-08 | 2,251E-07 |

| Emissions to air | Unit | Case NO | Case SE |
|---|---|---|---|
| Formic acid | kg | 6,925E-10 | 2,336E-09 |
| Heptane | kg | 3,528E-08 | 1,036E-07 |
| Hexane | kg | 8,366E-08 | 2,492E-07 |
| Hydrocarbons, unspecified | kg | 4,322E-07 | 1,459E-06 |
| Isoprene | kg | 9,113E-12 | 3,074E-11 |
| m-Xylene | kg | 3,372E-10 | 1,136E-09 |
| Methane | kg | 1,099E-05 | 3,706E-05 |
| Methane, biogenic | kg | 9,938E-07 | 3,352E-06 |
| Methane, bromo-, Halon 1001 | kg | 2,784E-18 | 9,396E-18 |
| Methane, bromochlorodifluoro-, Halon 1211 | kg | 2,985E-11 | 1,003E-10 |
| Methane, bromotrifluoro-, Halon 1301 | kg | 9,537E-11 | 2,819E-10 |
| Methane, chlorodifluoro-, HCFC-22 | kg | 1,148E-10 | 3,86E-10 |
| Methane, dichloro-, HCC-30 | kg | 2,039E-12 | 6,877E-12 |
| Methane, dichlorodifluoro-, CFC-12 | kg | 4,285E-10 | 1,446E-09 |
| Methane, dichlorofluoro-, HCFC-21 | kg | 1,264E-16 | 4,266E-16 |
| Methane, fossil | kg | 1,599E-05 | 5,213E-05 |
| Methane, monochloro-, R-40 | kg | 1,347E-12 | 4,542E-12 |
| Methane, tetrachloro-, CFC-10 | kg | 1,603E-10 | 5,407E-10 |
| Methane, tetrafluoro-, CFC-14 | kg | 3,533E-09 | 1,192E-08 |
| Methane, trichlorofluoro-, CFC-11 | kg | 2,052E-16 | 6,925E-16 |
| Methane, trifluoro-, HFC-23 | kg | 4,022E-14 | 1,357E-13 |
| Methanol | kg | 6,666E-08 | 2,247E-07 |
| Methyl ethyl ketone | kg | 1,842E-07 | 6,215E-07 |
| Methyl formate | kg | 1,798E-15 | 6,067E-15 |
| Nitrate | kg | 1,459E-11 | 4,921E-11 |
| Nitric oxide | kg | 1,7E-12 | 5,736E-12 |
| Nitrogen dioxide | kg | 7,141E-16 | 2,41E-15 |
| Nitrogen oxides | kg | 0,0001275 | 0,0003671 |
| NMVOC, non-methane volatile organic compounds | kg | 9,673E-06 | 3,044E-05 |
| Octane | kg | 3,246E-11 | 1,095E-10 |
| Pentane | kg | 2,551E-07 | 7,772E-07 |
| Phosphorus | kg | 2,443E-09 | 8,24E-09 |
| Propanal | kg | 8,513E-12 | 2,867E-11 |
| Propane | kg | 2,051E-07 | 6,234E-07 |
| Propene | kg | 2,62E-08 | 8,53E-08 |
| Propionic acid | kg | 3,403E-10 | 1,146E-09 |
| Styrene | kg | 5,786E-11 | 1,951E-10 |
| Sulfur dioxide | kg | 2,404E-05 | 7,677E-05 |
| Sulfur hexafluoride | kg | 2,864E-10 | 9,599E-10 |
| Sulfur oxides | kg | 6,422E-05 | 0,0002082 |
| t-Butyl methyl ether | kg | 2,697E-12 | 9,101E-12 |
| Toluene | kg | 3,525E-08 | 1,092E-07 |

**TABLE A23: EMISSIONS TO WATER CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES**

| Substance | Unit | Case NO | Case SE |
|---|---|---|---|
| Ammonia | kg | 1,98E-11 | 6,68E-11 |
| Ammonium, ion | kg | 9,26E-07 | 3,12E-06 |
| COD, Chemical Oxygen Demand | kg | 7,91E-05 | 2,51E-04 |
| Nitrate | kg | 4,95E-06 | 1,67E-05 |
| Nitrite | kg | 5,00E-08 | 1,69E-07 |
| Nitrogen | kg | 5,52E-07 | 1,86E-06 |
| Nitrogen, total | kg | 2,28E-06 | 7,69E-06 |
| Phosphate | kg | 9,27E-07 | 3,13E-06 |
| Phosphorus | kg | 4,14E-08 | 1,39E-07 |
| Phosphorus, total | kg | 5,45E-10 | 1,84E-09 |

**TABLE A24: EMISSIONS TO SOIL CONTRIBUTING TO ENVIRONMENTAL IMPACT CATEGORIES**

| Substance | Unit | Case NO | Case SE |
|---|---|---|---|
| Ammonia | kg | 2,47E-09 | 8,32E-09 |
| Phosphorus | kg | 3,88E-09 | 1,31E-08 |

# APPENDIX 3: CHARACTERIZATION FACTORS

**TABLE A31: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO GLOBAL WARMING**

| Global warming (GWP100) | | | |
|---|---|---|---|
| **Category** | **Substance** | **CAS-number** | **[kg CO2 eq/kg]** |
| Air | 1H,1H,2H,2H-Perfluorohexan-1-ol, HFE-7200 | 002043-47-2 | 55 |
| Air | Benzaldehyde | 000100-52-7 | -0,092 |
| Air | Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc | 000406-58-6 | 890 |
| Air | Butane, nonafluoromethoxy, HFE-7100 | 163702-07-6 | 390 |
| Air | Butane, perfluoro- | 000355-25-9 | 8600 |
| Air | Butane, perfluorocyclo-, PFC-318 | 000115-25-3 | 10000 |
| Air | Carbon dioxide | 000124-38-9 | 1 |
| Air | Carbon dioxide, fossil | 000124-38-9 | 1 |
| Raw | Carbon dioxide, in air | 000124-38-9 | -1 |
| Air | Carbon dioxide, land transformation | 000124-38-9 | 1 |
| Air | Chloroform | 000067-66-3 | 30 |
| Air | Dimethyl ether | 000115-10-6 | 1 |
| Air | Dinitrogen monoxide | 010024-97-2 | 296 |
| Air | Ethane, 1-chloro-1,1-difluoro-, HCFC-142b | 000075-68-3 | 2400 |
| Air | Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2 | 026675-46-7 | 340 |
| Air | Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b | 001717-00-6 | 700 |
| Air | Ethane, 1,1-difluoro-, HFC-152a | 000075-37-6 | 120 |
| Air | Ethane, 1,1,1-trichloro-, HCFC-140 | 000071-55-6 | 140 |
| Air | Ethane, 1,1,1-trifluoro-, HFC-143a | 000420-46-2 | 4300 |
| Air | Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | 000811-97-2 | 1300 |
| Air | Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 | 000076-13-1 | 6000 |
| Air | Ethane, 1,1,2-trifluoro-, HFC-143 | 000430-66-0 | 330 |
| Air | Ethane, 1,1,2,2-tetrafluoro-, HFC-134 | 000359-35-3 | 1100 |
| Air | Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 | 000076-14-2 | 9800 |
| Air | Ethane, 1,2-difluoro-, HFC-152 | 000624-72-6 | 43 |
| Air | Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124 | 002837-89-0 | 620 |
| Air | Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123 | 000306-83-2 | 120 |
| Air | Ethane, chloropentafluoro-, CFC-115 | 000076-15-3 | 7200 |
| Air | Ethane, fluoro-, HFC-161 | 000353-36-6 | 12 |
| Air | Ethane, hexafluoro-, HFC-116 | 000076-16-4 | 11900 |
| Air | Ethane, pentafluoro-, HFC-125 | 000354-33-6 | 3400 |
| Air | Ethanol, 2,2,2-trifluoro- | 000075-89-8 | 57 |
| Air | Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcc3 | 000406-78-0 | 480 |
| Air | Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2 | 000425-88-7 | 30 |
| Air | Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3 | 000382-34-3 | 430 |
| Air | Ether, di(difluoromethyl), HFE-134 | 001691-17-4 | 6100 |
| Air | Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2 | 001885-48-9 | 580 |
| Air | Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2 | 001885-48-9 | 570 |
| Air | Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE-374pc2 | 000512-51-6 | 540 |
| Air | Ether, pentafluoromethyl-, HFE-125 | 003822-68-2 | 14900 |
| Air | H-Galden 1040x | | 1800 |
| Air | Hexane, perfluoro- | 000355-42-0 | 9000 |
| Air | HFE-236ca12 (HG-10) | | 2700 |

| | | | |
|---|---|---|---|
| Air | HG-01 | | 1500 |
| Air | Methane | 000074-82-8 | 23 |

**Global warming (GWP100)**

| Category | Substance | CAS-number | [kg CO2 eq/kg] |
|---|---|---|---|
| Air | Methane, bromo-, Halon 1001 | 000074-83-9 | 5 |
| Air | Methane, bromochlorodifluoro-, Halon 1211 | 000353-59-3 | 1300 |
| Air | Methane, bromodifluoro-, Halon 1201 | 001511-62-2 | 470 |
| Air | Methane, bromotrifluoro-, Halon 1301 | 000075-63-8 | 6900 |
| Air | Methane, chlorodifluoro-, HCFC-22 | 000075-45-6 | 1700 |
| Air | Methane, chlorotrifluoro-, CFC-13 | 000075-72-9 | 14000 |
| Air | Methane, dibromo- | 000074-95-3 | 1 |
| Air | Methane, dichloro-, HCC-30 | 000075-09-2 | 10 |
| Air | Methane, dichlorodifluoro-, CFC-12 | 000075-71-8 | 10600 |
| Air | Methane, dichlorofluoro-, HCFC-21 | 000075-43-4 | 210 |
| Air | Methane, difluoro-, HFC-32 | 000075-10-5 | 550 |
| Air | Methane, fluoro-, HFC-41 | 000593-53-3 | 97 |
| Air | Methane, fossil | 000074-82-8 | 23 |
| Air | Methane, iodotrifluoro- | 002314-97-8 | 1 |
| Air | Methane, monochloro-, R-40 | 000074-87-3 | 16 |
| Air | Methane, tetrachloro-, CFC-10 | 000056-23-5 | 1800 |
| Air | Methane, tetrafluoro-, CFC-14 | 000075-73-0 | 5700 |
| Air | Methane, trichlorofluoro-, CFC-11 | 000075-69-4 | 4600 |
| Air | Methane, trifluoro-, HFC-23 | 000075-46-7 | 12000 |
| Air | Methane, trifluoro-methoxy-, HFE-143a | | 750 |
| Air | Pentane, 2,3-dihydroperfluoro-, HFC-4310mee | 138495-42-8 | 1500 |
| Air | Pentane, perfluoro- | 000678-26-2 | 8900 |
| Air | Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb | 000677-56-5 | 1300 |
| Air | Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea | 000431-63-0 | 1200 |
| Air | Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea | 000431-89-0 | 3500 |
| Air | Propane, 1,1,1,3,3-pentafluoro-, HFC-245fa | 000460-73-1 | 950 |
| Air | Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa | 000690-39-1 | 9400 |
| Air | Propane, 1,1,1,3,3,3-hexafluoro-2-(fluoromethoxy)- | | 330 |
| Air | Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca | 000679-86-7 | 640 |
| Air | Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb | 000507-55-1 | 620 |
| Air | Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca | 000422-56-0 | 180 |
| Air | Propane, perfluoro- | 000076-19-7 | 8600 |
| Air | Propanol, 1,1,1,3,3,3-hexafluoro-2- | 000920-66-1 | 190 |
| Air | Propanol, pentafluoro-1- | 000422-05-9 | 40 |
| Air | Sulfur hexafluoride | 002551-62-4 | 22200 |

#### TABLE A32: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO OZONE LAYER DEPLETION

| Ozone layer depletion (ODP) | | | |
|---|---|---|---|
| Category | Substance | CAS-number | [kg CFC-11 eq/kg] |
| Air | Ethane, 1-chloro-1,1-difluoro-, HCFC-142b | 000075-68-3 | 0,14 |
| Air | Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b | 001717-00-6 | 0,33 |
| Air | Ethane, 1,1,1-trichloro-, HCFC-140 | 000071-55-6 | 0,45 |
| Air | Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 | 000076-13-1 | 0,59 |
| Air | Ethane, 1,2-dibromotetrafluoro-, Halon 2402 | 000124-73-2 | 11 |
| Air | Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124 | 002837-89-0 | 0,08 |
| Air | Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123 | 000306-83-2 | 0,08 |
| Air | Methane, bromo-, Halon 1001 | 000074-83-9 | 2,3 |
| Air | Methane, bromochlorodifluoro-, Halon 1211 | 000353-59-3 | 9 |
| Air | Methane, bromotrifluoro-, Halon 1301 | 000075-63-8 | 10,5 |
| Air | Methane, chlorodifluoro-, HCFC-22 | 000075-45-6 | 0,14 |
| Air | Methane, tetrachloro-, CFC-10 | 000056-23-5 | 1,23 |
| Air | Methane, trichlorofluoro-, CFC-11 | 000075-69-4 | 1 |
| Air | Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb | 000507-55-1 | 0,11 |
| Air | Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca | 000422-56-0 | 0,1 |

#### TABLE A33: CHARACTERIZATION FACTORS FOR SUBSTANCES CONTRIBUTING TO PHOTOCHEMICAL OXIDATION

| Photochemical oxidation | | | |
|---|---|---|---|
| Category | Substance | CAS-number | [kg C2H4-eq/kg] |
| Air | 1-Butanol | 000071-36-3 | 0,62 |
| Air | 1-Butene | 000106-98-9 | 1,079 |
| Air | 1-Butene, 2-methyl- | 000563-46-2 | 0,771 |
| Air | 1-Butene, 3-methyl- | 000563-45-1 | 0,671 |
| Air | 1-Hexene | 000592-41-6 | 0,874 |
| Air | 1-Pentene | 000109-67-1 | 0,977 |
| Air | 1-Propanol | 000071-23-8 | 0,561 |
| Air | 2-Butanol | 000078-92-2 | 0,4 |
| Air | 2-Butanone, 3-methyl- | 000563-80-4 | 0,364 |
| Air | 2-Butanone, 3,3-dimethyl- | 000075-97-8 | 0,323 |
| Air | 2-Butene (cis) | 000590-18-1 | 1,146 |
| Air | 2-Butene (trans) | 000624-64-6 | 1,132 |
| Air | 2-Hexanone | 000591-78-6 | 0,572 |
| Air | 2-Hexene (cis) | 007688-21-3 | 1,069 |
| Air | 2-Hexene (trans) | 004050-45-7 | 1,073 |
| Air | 2-Methyl-1-propanol | 000078-83-1 | 0,36 |
| Air | 2-Methyl-2-butene | 000513-35-9 | 0,842 |
| Air | 2-Methyl pentane | 000107-83-5 | 0,42 |
| Air | 2-Pentanone | 000107-87-9 | 0,548 |
| Air | 2-Pentene (cis) | 000627-20-3 | 1,121 |
| Air | 2-Pentene (trans) | 000646-04-8 | 1,117 |
| Air | 2-Propanol | 000067-63-0 | 0,188 |
| Air | 3-Hexanone | 000589-38-8 | 0,599 |
| Air | 3-Methyl-1-butanol | 000123-51-3 | 0,433 |
| Air | 3-Pentanol | 000584-02-1 | 0,595 |
| Air | 4-Methyl-2-pentanone | 000108-10-1 | 0,49 |
| Air | Acetaldehyde | 000075-07-0 | 0,641 |
| Air | Acetic acid | 000064-19-7 | 0,097 |
| Air | Acetic acid, methyl ester | 000079-20-9 | 0,059 |
| Air | Acetic acid, propyl ester | 000109-60-4 | 0,282 |
| Air | Acetone | 000067-64-1 | 0,094 |

| | | | |
|---|---|---|---|
| Air | Alcohol, diacetone | 000123-42-2 | 0,307 |
| Air | Benzaldehyde | 000100-52-7 | -0,092 |

**Photochemical oxidation**

| Category | Substance | CAS-number | [kg C2H4-eq/kg] |
|---|---|---|---|
| Air | Benzene, 1,2,3-trimethyl- | 000526-73-8 | 1,267 |
| Air | Benzene, 1,2,4-trimethyl- | 000095-63-6 | 1,278 |
| Air | Benzene, 1,3,5-trimethyl- | 000108-67-8 | 1,381 |
| Air | Benzene, 3,5-dimethylethyl- | 000934-74-7 | 1,32 |
| Air | Benzene, ethyl- | 000100-41-4 | 0,73 |
| Air | Butadiene | 000106-99-0 | 0,851 |
| Air | Butanal | 000123-72-8 | 0,795 |
| Air | Butane | 000106-97-8 | 0,352 |
| Air | Butane, 2,2-dimethyl- | 000075-83-2 | 0,241 |
| Air | Butane, 2,3-dimethyl- | 000079-29-8 | 0,541 |
| Air | Butanol, 2-methyl-1- | 000137-32-6 | 0,489 |
| Air | Butanol, 2-methyl-2- | 000075-85-4 | 0,228 |
| Air | Butanol, 3-methyl-2- | 000598-75-4 | 0,406 |
| Air | Butyl acetate | 000123-86-4 | 0,269 |
| Air | Chloroform | 000067-66-3 | 0,023 |
| Air | Cumene | 000098-82-8 | 0,5 |
| Air | Cyclohexane | 000110-82-7 | 0,29 |
| Air | Cyclohexanol | 000108-93-0 | 0,518 |
| Air | Cyclohexanone | 000108-94-1 | 0,299 |
| Air | Decane | 000124-18-5 | 0,384 |
| Air | Diethyl ether | 000060-29-7 | 0,445 |
| Air | Diethyl ketone | 000096-22-0 | 0,414 |
| Air | Diisopropyl ether | 000108-20-3 | 0,398 |
| Air | Dimethyl carbonate | 000616-38-6 | 0,025 |
| Air | Dimethyl ether | 000115-10-6 | 0,189 |
| Air | Dodecane | 000112-40-3 | 0,357 |
| Air | Ethane | 000074-84-0 | 0,123 |
| Air | Ethane, 1,1,1-trichloro-, HCFC-140 | 000071-55-6 | 0,009 |
| Air | Ethanol | 000064-17-5 | 0,399 |
| Air | Ethanol, 2-butoxy- | 000111-76-2 | 0,483 |
| Air | Ethanol, 2-methoxy- | 000109-86-4 | 0,307 |
| Air | Ethene | 000074-85-1 | 1 |
| Air | Ethene, dichloro- (cis) | 000156-59-2 | 0,447 |
| Air | Ethene, dichloro- (trans) | 000156-60-5 | 0,392 |
| Air | Ethene, tetrachloro- | 000127-18-4 | 0,029 |
| Air | Ethene, trichloro- | 000079-01-6 | 0,325 |
| Air | Ethyl acetate | 000141-78-6 | 0,209 |
| Air | Ethylene glycol | 000107-21-1 | 0,373 |
| Air | Ethylene glycol monoethyl ether | 000110-80-5 | 0,386 |
| Air | Ethyne | 000074-86-2 | 0,085 |
| Air | Formaldehyde | 000050-00-0 | 0,519 |
| Air | Formic acid | 000064-18-6 | 0,032 |
| Air | Heptane | 000142-82-5 | 0,494 |
| Air | Hexane | 000110-54-3 | 0,482 |
| Air | Hexane, 2-methyl- | 000591-76-4 | 0,411 |
| Air | Hexane, 3-methyl- | 000589-34-4 | 0,364 |
| Air | Hydrocarbons, unspecified | | 0,337 |
| Air | Isobutane | 000075-28-5 | 0,307 |
| Air | Isobutene | 000115-11-7 | 0,627 |
| Air | Isobutyraldehyde | 000078-84-2 | 0,514 |
| Air | Isopentane | 000078-78-4 | 0,405 |
| Air | Isoprene | 000078-79-5 | 1,092 |
| Air | Isopropyl acetate | 000108-21-4 | 0,211 |
| Air | m-Xylene | 000108-38-3 | 1,108 |
| Air | Methane | 000074-82-8 | 0,006 |
| Air | Methane, biogenic | 000074-82-8 | 0,006 |

| | | | |
|---|---|---|---|
| Air | Methane, dichloro-, HCC-30 | 000075-09-2 | 0,068 |
| Air | Methane, dimethoxy- | 000109-87-5 | 0,164 |

| **Photochemical oxidation** | | | |
|---|---|---|---|
| **Category** | **Substance** | **CAS-number** | **[kg C2H4-eq/kg]** |
| Air | Methane, fossil | 000074-82-8 | 0,006 |
| Air | Methane, monochloro-, R-40 | 000074-87-3 | 0,005 |
| Air | Methanol | 000067-56-1 | 0,14 |
| Air | Methyl ethyl ketone | 000078-93-3 | 0,373 |
| Air | Methyl formate | 000107-31-3 | 0,027 |
| Air | Nitric oxide | 010102-43-9 | -0,427 |
| Air | Nitrogen dioxide | 010102-44-0 | 0,028 |
| Air | NMVOC, non-methane volatile organic compounds | | 1 |
| Air | Nonane | 000111-84-2 | 0,414 |
| Air | o-Xylene | 000095-47-6 | 1,053 |
| Air | Octane | 000111-65-9 | 0,453 |
| Air | p-Xylene | 000106-42-3 | 1,01 |
| Air | Pentanal | 000110-62-3 | 0,765 |
| Air | Pentane | 000109-66-0 | 0,395 |
| Air | Pentane, 3-methyl- | 000096-14-0 | 0,479 |
| Air | Petrol | 008006-61-9 | 0,42 |
| Air | Propanal | 000123-38-6 | 0,798 |
| Air | Propane | 000074-98-6 | 0,176 |
| Air | Propane, 2,2-dimethyl- | 000463-82-1 | 0,173 |
| Air | Propene | 000115-07-1 | 1,123 |
| Air | Propionic acid | 000079-09-4 | 0,15 |
| Air | Propylene glycol | 000057-55-6 | 0,457 |
| Air | Propylene glycol methyl ether | 000107-98-2 | 0,355 |
| Air | Propylene glycol t-butyl ether | 057018-52-7 | 0,463 |
| Air | s-Butyl acetate | 000105-46-4 | 0,275 |
| Air | Styrene | 000100-42-5 | 0,14 |
| Air | Sulfur dioxide | 007446-09-5 | 0,048 |
| Air | Sulfur oxides | | 0,048 |
| Air | t-Butyl acetate | 000540-88-5 | 0,053 |
| Air | t-Butyl alcohol | 000075-65-0 | 0,106 |
| Air | t-Butyl ethyl ether | 000637-92-3 | 0,244 |
| Air | t-Butyl methyl ether | 001634-04-4 | 0,175 |
| Air | Toluene | 000108-88-3 | 0,637 |
| Air | Toluene, 2-ethyl- | 000611-14-3 | 0,898 |
| Air | Toluene, 3-ethyl- | 000620-14-4 | 1,019 |
| Air | Toluene, 3,5-diethyl- | 002050-24-0 | 1,295 |
| Air | Toluene, 4-ethyl- | 000622-96-8 | 0,906 |
| Air | Undecane | 001120-21-4 | 0,384 |

**TABLE A34: CHARACTERIZATION FACTORS FOR EMISSIONS CONTRIBUTING TO ACIDIFICATION**

| **Acidification** | | | |
|---|---|---|---|
| **Category** | **Substance** | **CAS-number** | **[kg SO2-eq/kg]** |
| Air | Ammonia | 007664-41-7 | 1,6 |
| Air | Nitrogen dioxide | 010102-44-0 | 0,5 |
| Air | Nitrogen oxides | 011104-93-1 | 0,5 |
| Air | Sulfur dioxide | 007446-09-5 | 1 |
| Air | Sulfur oxides | | 1 |

**TABLE A35: CHARACTERIZATION FACTORS FOR EMISSIONS CONTRIBUTING TO EUTROPHICATION**

| Eutrophication Category | Substance | CAS-number | [kg PO4-eq / kg] |
|---|---|---|---|
| Air | Ammonia | 007664-41-7 | 0,35 |
| Water | Ammonia | 007664-41-7 | 0,35 |
| Soil | Ammonia | 007664-41-7 | 0,35 |
| Air | Ammonium carbonate | 000506-87-6 | 0,12 |
| Air | Ammonium nitrate | 006484-52-2 | 0,074 |
| Soil | Ammonium nitrate | 006484-52-2 | 0,074 |
| Air | Ammonium, ion | 014798-03-9 | 0,33 |
| Water | Ammonium, ion | 014798-03-9 | 0,33 |
| Soil | Ammonium, ion | 014798-03-9 | 0,33 |
| Water | COD, Chemical Oxygen Demand | | 0,022 |
| Air | Dinitrogen monoxide | 010024-97-2 | 0,13 |
| Water | Dinitrogen monoxide | 010024-97-2 | 0,13 |
| Soil | Dinitrogen monoxide | 010024-97-2 | 0,13 |
| Air | Nitrate | 014797-55-8 | 0,1 |
| Water | Nitrate | 014797-55-8 | 0,1 |
| Soil | Nitrate | 014797-55-8 | 0,1 |
| Air | Nitric acid | 007697-37-2 | 0,1 |
| Water | Nitric acid | 007697-37-2 | 0,1 |
| Soil | Nitric acid | 007697-37-2 | 0,1 |
| Air | Nitric oxide | 010102-43-9 | 0,2 |
| Water | Nitrite | 014797-65-0 | 0,1 |
| Water | Nitrogen | 007727-37-9 | 0,42 |
| Air | Nitrogen dioxide | 010102-44-0 | 0,13 |
| Air | Nitrogen oxides | 011104-93-1 | 0,13 |
| Water | Nitrogen oxides | 011104-93-1 | 0,13 |
| Soil | Nitrogen oxides | 011104-93-1 | 0,13 |
| Air | Nitrogen, total | | 0,42 |
| Water | Nitrogen, total | | 0,42 |
| Soil | Nitrogen, total | | 0,42 |
| Air | Phosphate | 014265-44-2 | 1 |
| Water | Phosphate | 014265-44-2 | 1 |
| Soil | Phosphate | 014265-44-2 | 1 |
| Air | Phosphoric acid | 007664-38-2 | 0,97 |
| Water | Phosphoric acid | 007664-38-2 | 0,97 |
| Soil | Phosphoric acid | 007664-38-2 | 0,97 |
| Air | Phosphorus | 007723-14-0 | 3,06 |
| Water | Phosphorus | 007723-14-0 | 3,06 |
| Soil | Phosphorus | 007723-14-0 | 3,06 |
| Air | Phosphorus pentoxide | 001314-56-3 | 1,34 |
| Water | Phosphorus pentoxide | 001314-56-3 | 1,34 |
| Soil | Phosphorus pentoxide | 001314-56-3 | 1,34 |
| Air | Phosphorus, total | | 3,06 |
| Water | Phosphorus, total | | 3,06 |
| Soil | Phosphorus, total | | 3,06 |

**TABLE A36: GROSS CALORIFIC VALUES OF NON-RENEWABLE ENERGY RESOURCES**

| Non-renewable energy<br>Substance | CAS-number | Gross Calorific Value | Unit |
|---|---|---|---|
| Coal, 18 MJ per kg, in ground | | 25,3 | MJ eq / kg |
| Coal, 26.4 MJ per kg, in ground | | 30 | MJ eq / kg |
| Coal, 29.3 MJ per kg, in ground | | 30 | MJ eq / kg |
| Coal, brown (lignite) | | 20 | MJ eq / kg |
| Coal, brown, 10 MJ per kg, in ground | | 25,3 | MJ eq / kg |
| Coal, brown, 8 MJ per kg, in ground | | 25,3 | MJ eq / kg |
| Coal, brown, in ground | | 25,3 | MJ eq / kg |
| Coal, feedstock, 26.4 MJ per kg, in ground | | 25,3 | MJ eq / kg |
| Coal, hard, unspecified, in ground | | 30 | MJ eq / kg |
| Gas, mine, off-gas, process, coal mining/kg | 008006-14-2 | 43,1 | MJ eq / kg |
| Gas, mine, off-gas, process, coal mining/m3 | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, natural (0,8 kg/m3) | 008006-14-2 | 30 | MJ eq / m3 |
| Gas, natural, 30.3 MJ per kg, in ground | 008006-14-2 | 43,1 | MJ eq / kg |
| Gas, natural, 35 MJ per m3, in ground | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, natural, 36.6 MJ per m3, in ground | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, natural, 46.8 MJ per kg, in ground | 008006-14-2 | 43,1 | MJ eq / kg |
| Gas, natural, feedstock, 35 MJ per m3, in ground | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, natural, feedstock, 46.8 MJ per kg, in ground | 008006-14-2 | 43,1 | MJ eq / kg |
| Gas, natural, in ground | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, off-gas, oil production, in ground | 008006-14-2 | 39 | MJ eq / m3 |
| Gas, petroleum, 35 MJ per m3, in ground | | 39 | MJ eq / m3 |
| Methane | 000074-82-8 | 55,52 | MJ eq / kg |
| Oil, crude, 38400 MJ per m3, in ground | | 42158 | MJ eq / m3 |
| Oil, crude, 41 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, 42 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, 42.6 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, 42.7 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, feedstock, 41 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, feedstock, 42 MJ per kg, in ground | | 43,76 | MJ eq / kg |
| Oil, crude, in ground | | 43,76 | MJ eq / kg |
| Uranium, in ground | 007440-61-1 | 451000 | MJ eq / kg |

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