NTNU – Trondheim
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Science and Technology

# Life Cycle Assessment of Farmed Salmon, Comparing a Closed with an Open Sea Cage System

Ole Jonny Nyhus

Marine Technology
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Supervisor: Harald Ellingsen, IMT
Co-supervisor: Svein Aanond Aanondsen, IMT

Norwegian University of Science and Technology
Department of Marine Technology

**NTNU**
**Norwegian University of Science and Technology**

**IVT-Faculty,**
**Institute of Marine Technology**

## TMR4930 - Master Thesis Marine Systems - Spring 2014

Stud. tech. Ole Jonny Nyhus

# Life Cycle Assessment of Farmed Salmon, Comparing a Closed with an Open Sea Cage System

Livssyklusanalyse av lukket oppdrettsanlegg. En sammenligning av åpent og lukket oppdrettsanlegg

**Background** The amount of fish farmed in Norway has tripled over the last 15 years, and Norwegian aquaculture has become a 30 billion kroner industry. This massive production increase makes it increasingly important to understand the environmental impacts the industry creates.

As an example, Norwegian fish farms are struggling with resistant salmon lice, and farms might be forced to slaughter the salmon earlier than wanted. This might create a strong incentive for developing and testing out new solutions that might solve the problem. The company Aquafuture in Brønnøysund is developing a closed fish cage solution for use in the Norwegian fish farming industry. This closed system, which collects the water from a depth too deep for the salmon lice, might be a possible solution to the lice problem. The system is now being tested on a fish farm located at Møllebogen in Bindal commune, in the middle of Norway. If this system is technologically and economically viable, we might see a push towards closed fish cage use in aquaculture. It is therefore an interesting question to ask, how environmentally friendly such a solution might be compared to the open cage systems of today?

This master thesis covers a life cycle assessment (LCA) comparing a closed and an open fish farm system used in salmon farming today. Another goal is to find key environmental impact areas for the closed cage system, such that environmental improvements can be made.

**Scope of Work** In this master thesis the candidates shall perform the following main activities:

- Describe "state the art" within closed fish farm systems and relevant LCA theory
- Develop a LCA comparing closed with open fish farms. The LCA shall cover the following steps:
  - Goal and scope phase
  - Life cycle inventory of closed and open system
  - Life cycle impact assessment
  - Life cycle interpretation
- Discuss the results and conclude with respect to the environmental impact of the two systems in light of technological development, what are causing the main environmental impacts and need for further work

**General** The work shall be carried out and reported in accordance with guidelines, rules and regulations pertaining to the completion of a Master Thesis in engineering at NTNU.

The work shall be completed and delivered electronic by: June 10th, 2014.

Main advisor is Professor Harald Ellingsen, Department of Marin Technology, NTNU.

MTS, June 8th, 2013
Harald Ellingsen
professor

# Preface

This thesis concludes my Master of Technology education in Marine Technology at the Norwegian University of Science and Technology. The thesis was written the spring of 2014, at the Institute of Marine Technology, in collaboration with Akva Design/Future in Brønnøysund. The thesis has subject code TMR4930, and amounts to 30 ECTS points.

I would like to thank Professor Harald Ellingsen and Assistant Professor Svein Aanond Aanondsen for guidance and for nudging me in the direction of environmental science and LCA. A thank also goes to Anders Næss for his cooporation and help with data on the closed fish farm.

Ole Jonny Nyhus
Trondheim, June 8, 2014

## Abstract

Ole Jonny Nyhus, Marin teknikk, Norges teknisk-naturvitenskapelige universitet.

Masteroppgavesammendrag, levert 8. juni, 2014:

Livssyklusanalye av lukket oppdrettsanlegg, en sammeligning av åpent og lukket oppdrettsanlegg.

Målet med denne masteroppgaven er å gjennomføre en livssyklusanalyse (LCA) av et lukket oppdrettsanlegg og sammenligne resultatene med et åpent anlegg, for så å komme med anbefalinger og konklusjoner basert på resultatene.

Livssyklusanalyse er en metode som beregner de miljømessige konsekvensene ved produksjonen av et produkt eller en tjenest. I dette tilfelle ser vi på produksjonen av ett tonn laks ved levering til brønnbåt. Vi sammenligner i denne masteroppgaven produksjonen av ett tonn ved et åpent anlegg med ett tonn ved et lukket anlegg.

I første delen av masteroppgaven beskrives bakgrunnen for analysen, samt teorien bak livssyklusanalyse. Lukkede anlegg kan være en løsning for lusproblematikken i oppdrettsbransjen, grunderbedriften Akvafuture i Brønnøysund er i utvikling av et slikt anlegg, og de har gått med på å levere tall som kan brukes i analysen. Disse tallene sammen med tall fra andre store aktører i bransjen utgjør datagrunnlaget for livssyklusanalysen. Forgrunnsprosessene vi bruker i denne analysen er smolt- of fôrprodukjon, smolt- og fôrtransport, og oppdrettsanlegget. Kategoriene som dekkes i analysen er klima, forsuring, ferskvanns eutrofisering og marin økotoksisitet.

Analysen viste at det lukkede anlegget brukte en mye større elektrisk strømmengde enn det åpne anlegget, dette fra pumper og oksygenprodukjon. Dette gjør det lukkede anlegget veldig sensitiv for forandringer i de miljømessige konsekvensene fra strømmen, og det er derfor viktig å vite hvilken strømmiks som antas å brukes på anlegget. Ved anlegg i Norge utgjør denne ekstra strømmen lite, men konsekvensbidraget øker kraftig for klima og forsuringskategoriene når strømmen blir skitnere, f.eks. ved strøm fra Europa.

Fôrproduksjonen er den desidert mest bidragsytende når det kommer til de fire kategoriene vi har sett på i denne analysen. For ferskvanns eutrofisering og marin økotoksisitet utgjør fôret nesten hundre prosent av bidraget, mens for de to andre utgjør det 80 – 90%.

I konklusjon kan vi se at for norske forhold er lukkede anlegg et miljømessig godt alternativ når vi ser på kategoriene i analysen. Det kan argumenteres for andre fordeler som gjør lukkede anlegg overlegent et åpent anlegg, f.eks. ingen lus, bedre vekst, sunnere fisk mm., men lukkede anlegg har ennå til gode å bevise disse fordelene. Det bør sies dataene i denne analysen er fra veldig tidlige forsøk, og at fisken i disse forsøkene klarte å holde lusa unna.

**Abstract**

Ole Jonny Nyhus, Marine Technology, Norwegian University of Science and Technology.

Abstract of Master's Thesis, levert 8. juni, 2014:

Life Cycle Assessment of Farmed Salmon, Comparing a Closed with an Open Sea Cage System.

The goal of this Master's Thesis is to do a Life Cycle Assessment (LCA) on a closed fish farm system and compare it to an open fish farm system, for so to make recommendations based on the results.

Life Cycle Assessment is a method to calculate the environmental impacts that comes from producing a product or a service. In this case the product is one tonne of salmon at farm gate. We compare this with the impacts from producing one tonne at an open fish farm.

In the first part of the thesis we describe the reasons for carrying out the LCA, and the theory used. Closed fish farm systems might be the solution to the salmon lice problem the industry is facing, the developer Akvafuture in Brønnøysund is developing such a system, and the have agreed to deliver numbers for use in the LCA. These and numbers from big actors in the industry makes up the data used in the LCA. The foreground processes included in the study is smolt and feed production, smolt and feed transport, and the fish farm. The categories covered in the study is climate change, terrestrial acidification, freshwater eutrophication, and marine ecotoxicity.

The LCA showed that the closed system used alot more electric energy than the open system, this mainly from pumps and production of oxygen. This makes the impacts from the closed system sensitive to changes in impacts from the electric energy, it is therefore important to know what power is used on the fish farm. For farms in Norway this have little impacts due to the clean energy from Norwegian hydro power, but it increases for the climate and acidification category when the energy gets dirtier, e.g. by using Eurpean electricity mix.

The feed production is by far the most contributing process in all four categories. For freshwater eutrophication and marine ecotoxicity the contribution is almost a hundred percent of the impacts.

In conclusion we can see that for use in Norwegian waters and with Norwegian el-mix, the closed fish farm system is a environmentally good alternative to open fish farm systems when looking on the categories in this LCA. I can be argued that closed systems have other positive aspects like no lice, better feed factor, healthier fish and more, but has yet to be shown, and the closed systems have much yet to prove. It should be noted this LCA used data from early testing, and for that period the salmon was lice free.

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# Nomenclature

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| GWP | Global Warming Potential |
| TAP | Terrestrial Acidification Potential |
| FEP | Freshwater Eutrophication Potential |
| MET | Marine Ecotoxicity Potential |
| $CO_2$ | Carbon dioxide |
| $SO_2$ | Sulfur dioxide |
| P | Phosphorus |
| 1,4-DB | 1,4 dichlorobenzene |
| FCR | Feed Conversion Ratio (same as feed factor) |
| FF | Feed Factor |
| El-mix | Electricity Mix |
| NO | Norwegian El-mix |
| NORDEL | Nordic El-mix |
| RER | European El-mix |
| OXB | Oxygen bought |

# Part I

# Introduction & Theory

# 1 Introduction

In the last fifteen years, Norwegian salmon farming industry have grown at an astounding rate, producing 300 thousand tonnes in 1997 to over 1200 today [1]. With this growth ecological issues like parasites and illnesses have become part of the daily enterprise for farmers. One of the most critical problems Norwegian fish farms is facing is an increase of salmon lice in the farmed and the natural salmon population [2]. The salmon louse (Lepeophtheirus salmonis) is a parasite found naturally in Norwegian waters, living of the skin and the blood of the salmonid species, e.g. salmon and rainbow trout [3] [4]. While the correlation between the increase of salmon farming and the increase of salmon lice in the natural population is well founded [5–7], not every study agree that there is a causation between lice in salmon farms and decline in natural salmon population [8]. The fact that lice from the fish farms will cause increase of lice in the natural population is not disputed, the question is rather if the increase in lice among the natural salmon will cause a decline in population size. Whether or not this is the case, it's important for the industry to use the precautionary principle, and instigate countermeasures against the parasite.

The salmon lice is also financially harming the industry, costing Norwegian fish farms over 500 million NOK annually in direct loses and for countermeasures like chemical disinfection [3]. The summer of 2013 the lice infection of wild Sea Trout became so severe that several farms had to slaughter the salmon earlier than planned, some regions even needed a total stop in production to manage the problem [9]. The fish farm companies concedes that the way the industry is run today is not sustainable, and technological solutions are needed.

A possible solution to the lice problem is to isolate the farmed salmon from the surrounding waters using a closed fish farming system. This would greatly decrease the chances of infecting the farm population with the louse, seeing that a farm without lice would have to be infected from the external, i.e. the water which the lice travels through. A new design of such a farming system is being developed by the company Akvadesign in Brønnøysund, and is the system we are using as basis for this study.

The concept design, see figure 1, is based on holding the salmon in a bag in stead of a net pen. The water is pumped from 25m depth and injected into the bag at the top, creating a whirlpool effect that keeps it circulating. The water is released into the surrounding waters through a hole at the bottom of the bag. Two tubes carries the waste from the bottom of the bag onto land, one tube for dead fish, and one for the sediment that settles to the sides and drops down due to the circulation in the bag. The dead fish get collected by a grid so that it gets separated from the other sediment, it's then pumped up by use of compressed air. The sediments, i.e. the waste from the fish etc., gets collected in a separate compartment, and gets pumped to the surface.

The system need extra aquatic oxygenation, either in the form of liquid oxygen stored in tanks on land, or by machines that collects oxygen from the air and injects it into the water. Keeping the water oxygenated is key to maximize the growth of the salmon though the year [10].

To decrease the likelihood of salmon escaping the farm uses a fish net like the ones they use in open cage farming. This net encompasses the fish pen, that way should the fish get out of the bag they would not escape into the wild.

A study by the Veterinary Institute of Norway, studying the effects on the fish farmed in the closed system, was started in 2011. The study began with a seven month period where the fish was followed closely. Next the fish was split in two cages, one closed, and one open net pen. The study then had three types of set up; closed to closed; closed to open; and open to open (the fish from the nearby open net pen continued in the same pen). The fish was slaughtered the autumn of 2013. Regarding lice, the study concludes that there is possible to keep infection in the closed system close to zero all through the production cycle. Keeping the lice infection below the level where disinfection is required is important, and is a key driver for this new technology. Other issues like cold sores and damage on the fishes fins and gills needed to be addressed [11].

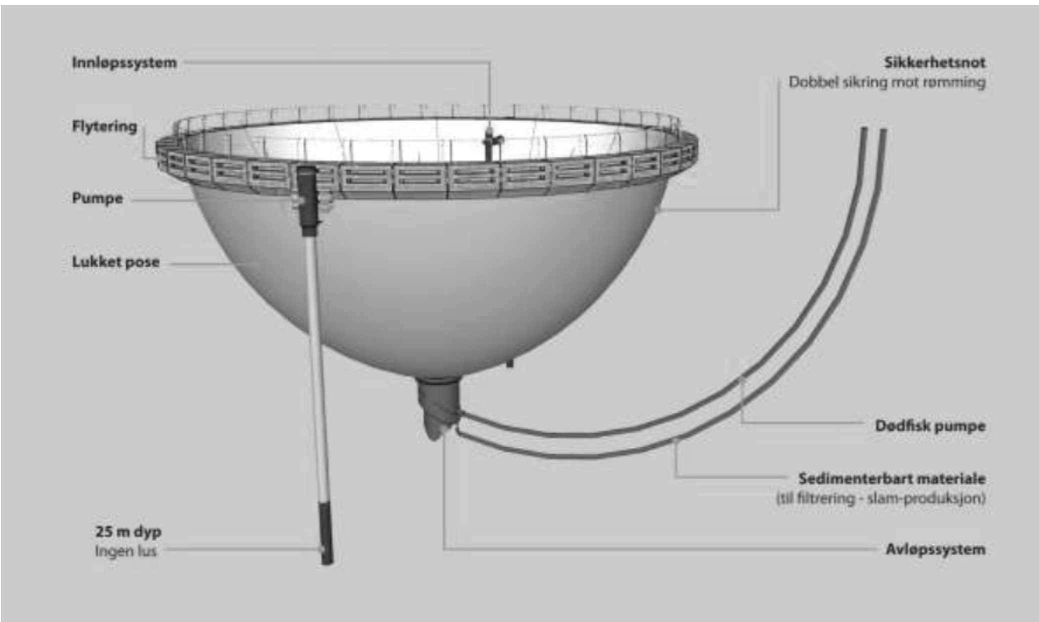


Figure 1: system design of closed fish farm

Technological issues aside, if this technology is viable to supplement or substitute the open net pens used in the industry today, it is important to compare the environmental impacts it may have compared to an open system. Studying the closed system rises questions regarding electricity use and feed conversion ratio, seeing that those two parameters might be what puts the two systems apart. Studies have shown that construction of the fish farm can be neglected [12], this was concluded due to it having small environmental impacts compared to rest of the fish farming cycle. Disregarding construction we might see that there is mostly the pumping and oxygenation of the water that is the obvious difference between the systems. If the cost of the pumping and oxygen production is large, then this could be a significant factor. A review done by Thorarensen et al. 2011 [10] found that salmon farmed in closed systems have a feed factor (FF) [1] of between 0.9 and 1.0, suggesting that FF is slightly lower for closed systems than for open systems, which have a mean of 1.02. Seeing that the feed production has been found to be the key component in studies on environmental impacts [13], this might favour the closed systems. This conclusion must be taken with a pinch of salt and it should be taken into account that the FCR varies greatly across geography and practice.

The basis for this Master Thesis is comparing the environmental impacts of the closed system developed in Brønnøysund with an open net pen. For this I will use Life Cycle Assessment methodology (LCA). The methodology of LCA was covered in my specialization project [14] written in the autumn of 2013, I will cite the paper throughout this thesis for reference, it can be found in Appendix D.

## 1.1 Life Cycle Assessment

LCA is a method for finding the environmental impacts from the production of a product. The impacts don't only stem from the production itself, but from the whole system of processes delivering resources to make the product, e.g. a simplified system like the one shown in figure 2. The emissions associated with the production of the salmon comes not only from the farming itself, but from a whole range of processes leading up to the fish farm, e.g. the electricity and feed production etc.. In this system the external demand for the product is the variable y. The y is called "the functional unit", the unit might be a fillet of salmon, or a kg of salmon depending on the system in question.

The arrows in the figure are resource requirements between two processes, it's them we need to find to calculate the environmental impacts the system creates. An example of resource requirement for a fish farm is feed.

The zigzagged arrows symbolizes the emissions from each process, an example of emission is carbon dioxide ($CO_2$). Emissions are divided into two categories, direct and indirect. The first are the emissions from each process viewed on their own, while the latter are the emissions created by the other processes as a result of the requirements from the process in question. For example a direct emission from producing a fillet of salmon might be

[1] Feed factor is the weight of feed divided on the weight of the fish produced

the excrements from the fish released into the surrounding waters, while an example of an indirect emission might be $CO_2$ stemming from the power plant burning gas to create electricity for the fish farm. The total emissions from a system are the sum of the direct and the indirect emissions, see eq. (1). By knowing these emissions we are able to calculate the environmental impacts stemming from the production of the functional unit, i.e. the fish in the case of the simplified system [15].

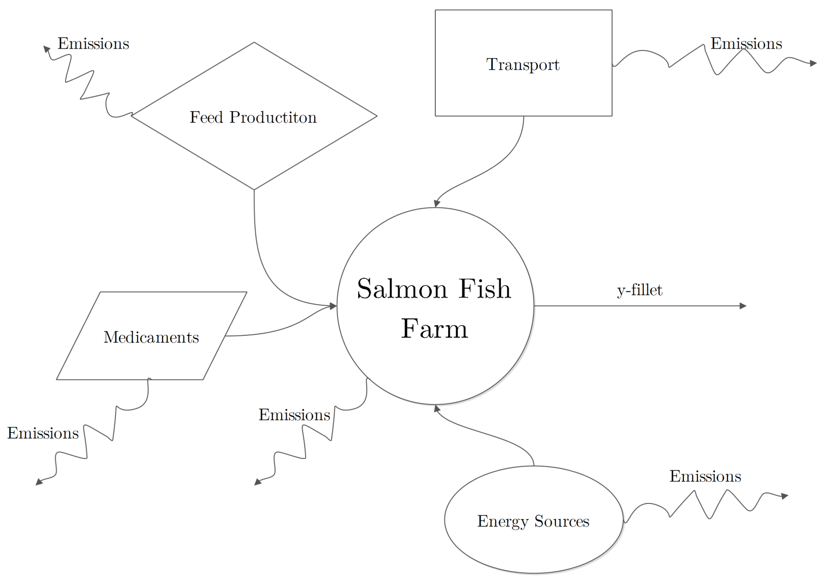


Figure 2: simplified salmon farming system

$$\text{Total emissions} = \text{Direct emissions} + \text{Indirect emissions} \tag{1}$$

#### 1.1.1 Four Phases

There are four phases in an LCA; the goal and scope phase, where we define how the study will be carried out; the life cycle inventory (LCI), where all the data is collected and structured; the life cycle impact assessment (LCIA), where the impacts from the system is quantified; and last the life cycle interpretation, where the results are discussed and interpreted. I will in the following section cover the theory needed to recreate the results of this study. It should be noted that all these phases have been covered in detail in my specialization project, in Appendix D.

# 2 Theory

## 2.1 Goal and Scope

### 2.1.1 Goal

The first phase in an LCA study is the goal and scope phase. The goal of the study is defined here; i.e. what is the reason to do the study, what will it be used for, and who is the audience. ISO14044 states that the goal of the study "shall unambiguously state the intended application, the reason for the study, and the intended audience" [16]. The scope of the study is chosen based on the goal of the study, therefore the goal of the study must be in place early [14, p. 5].

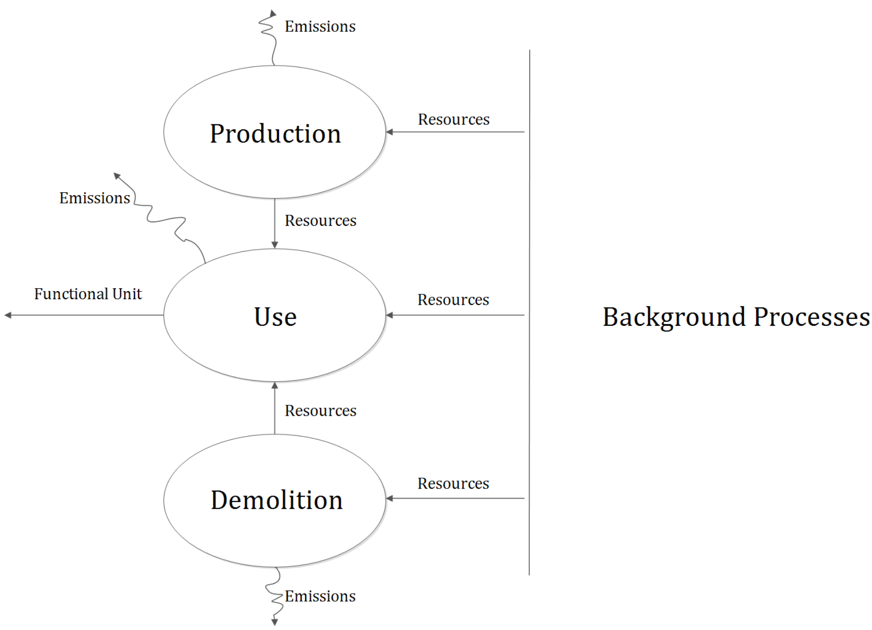


Figure 3: simple system with production, use and demolition phase, with use of background processes from background database such as Ecoinvent

### 2.1.2 Scope

The scope of the study is chosen based on the goal and includes the level of detail, what systems and processes that are included, functional unit, system boundary, impact categories, interpretation methods, and allocation methods [14, p. 5].

**Functional Unit** The functional unit is the reference unit which the whole study is based upon. It's the reference flow, meaning that all other flows in the modelled system relates to it. It has to be clearly defined and measurable [14, p. 6]. ISO14044 states that the functional unit shall be consistent with the goal and the scope of the study, and that the purpose of the functional unit is to provide a reference which the input and output data are normalized [16].

**System Boundary** The system boundary determines which processes and phases are included in the foreground system, and has to be consistent with the goal and the scope of the study [16]. The system boundary is usually described in a flow chart, which shows the different processes as nodes with flows of resources and materials between them [14, p. 6]. See figure 3 for an example of such a flow chart, also note the functional unit going from the main process.

**Impact Categories** This paper will use the ReCiPe 2008 life cycle impact assessment method [17]. It's a method based on Ecoindicator 99 and CML, using both mid- and endpoint category indicators. The method consists of the following impact categories [14, p. 7]:

- Climate Change (CC, GWP)
- Acidification (AP)
- Eutrophication (EP)
- Ozone Depletion (ODP)
- Toxicity (HT, ET)
- Human Health Damage Due to PM10 and Ozone
- Ionising Radiation
- Impacts of Land Use (LD)
- Water Depletion (WD)
- Mineral Resource Depletion (MRD)
- Fossil Fuel Depletion (FFD)

Due to the restrictions in the data collected this LCA will focus on four specific categories; Climate Change, also known as Global Warming Potential (GWP); Terrestrial

Acidification Potential (TAP), a subcategory of Acidification (AP); Freshwater Eutrophication Potential (FEP), a subcategory of Eutrophication (EP); and Marine Eco Toxicity (MET), a subcategory of Toxocity (ET) [14, p. 20] [17]. We will use midpoint characterization factor for all four categories.

Climate change is the category which handles all substances that contribute to the changing of the global climate. Global warming potential is the quantification of the warming effect a substance given in $CO_2$-equivalents. E.g. a substance can have larger or smaller impact per unit than $CO_2$, thus having a characterization factor larger or smaller than one, i.e. the midpoint characterization factor for $CO_2$ is one. See eq. 48 in Nyhus 2013 [14, p.20] for how the characterization factors for different substances is calculated. When doing the impact assessment the result for the climate change category is given in GWP which unit is kg of $CO_2$-equivalents.

Acidification is a decrease in pH in an environment. Terrestrial acidification is the quantification of the acidifying effect a substance have on the terrestrial environment given in $SO_2$-equivalents. See Nyhus 2013 [14, p. 20-22] on how it is calculated.

Eutrophication is the increase of nutrients, mainly phosphorus and nitrogen which is the limiting nutrients in waters. Freshwater eutrophication potential is the quantification of the category for freshwaters, given in phosphorus (P) equivalents. See Nyhus 2013 [14, p.22-23] on how it is calculated.

Toxicity is the damaging effect of a substance on biological organisms. Marine ecotoxicity is the quantification of the category for marine biological organisms and ecosystems, given in kg $1,4$-dichlorobenzene equivalents. See Nyhus 2013 [14, p.23-24] on how it is calculated.

See section on characterization methods in Nyhus 2013 [14, p. 20-] for a more complete coverage on the categories.

ISO states that the chosen impact categories shall be justified and consistent with the goal and scope of the study, and they shall reflect the environmental issues associated with the product [16]. The practitioner must also choose whether to use midpoint or endpoint characterization factors in the study, see Nyhus 2013 [14, p. 20-25] on midpoint and endpoint factors. In this study only midpoint characterization factors will be used. Midpoint factors have higher certainty, is easier to compute, and is therefore chosen for this study.

When the goal and the scope of the study has been defined the collection and structuring of data can start, called the LCI phase, which is covered next.

## 2.2 Life Cycle Inventory

The second phase of an LCA is the Life Cycle Inventory (LCI). In this phase all the required data gets collected from the different processes, e.g. requirements and emissions. Then the data is structured in the way required by the LCA method. The structure and logic behind the LCA method is covered in this section.

### 2.2.1 Leontief

The basic method used in LCA was first conceived by the economist Wassily Leontief in the nineteen seventies. For a thorough explanation on the method see Nyhus 2013 [14, p. 9-13], this section contains a shorter version of the theory.

The demands from a process required from another we call $a$, defined in eq. (2).

$$a_{ij} = \frac{\text{demand required from process}_{\text{ i}}}{\text{(per) unit output of process}_{\text{ j}}} \tag{2}$$

The external demand put on a process, i.e. the amount that goes out of the process but doesn't go to another process, we call $y$, defined in eq. (3).

$$y_i = \text{external demand put on process}_{\text{ i}} \tag{3}$$

The production from each process we call $x$, defined in eq. (4).

$$x_i = \text{units produced in process i for a required demand} \tag{4}$$

The interconnectivity of the system is shown in eq. (5). We see that the production of a process is dependent on the requirements from itself and from other processes, plus the external demand put on the process.

$$\begin{aligned} x_1 &= a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n + y_1 \\ x_2 &= a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n + y_2 \\ \vdots & \qquad\qquad \vdots \\ x_n &= a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n + y_n \end{aligned} \tag{5}$$

We see from this that the $x$'s and the $y$'s is vertical vectors $\mathbf{x}$ and $\mathbf{y}$, and the $a$'s is a matrix $\mathbf{A}$, the matrix is read as "from" on the rows, and "to" on the columns. The same interconnectivity as in eq. (5) is shown in vector form in eq. (6).

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{6}$$

It follows that $\mathbf{x}$ is defined as in eq. (7).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{7}$$

We call the first part of the right side the Leontief $\mathbf{L}$, defined in eq. (8) and (9) where n is the number of processes in the system.

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{8}$$

$$\mathbf{L} = \begin{pmatrix} 1 - a_{11} & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & 1 - a_{22} & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & 1 - a_{nn} \end{pmatrix}^{-1} \tag{9}$$

When the Leontief matrix is found, the next phase can begin.

### 2.2.2 Transport Modelling

In this LCA we will use the receiver input method to model transportation between processes. It works by making transport its own process within the foreground, see fig. 4 how this is modelled, here T2-1 is the transportation from process 2 to 1 [14, p. 13].

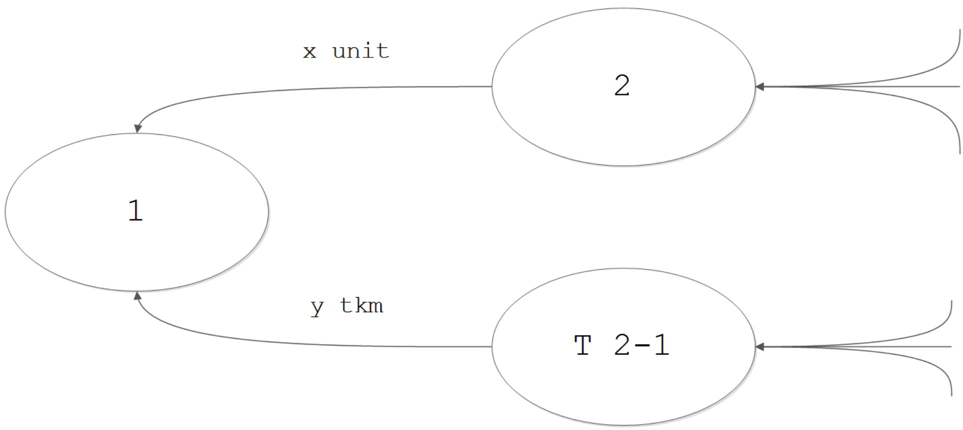


Figure 4: receiver input method for delivery of x units from process 1 to process 2, resulting in y tkm of transport

## 2.3 Life Cycle Impact Assessment

The third phase of an LCA is the Life Cycle Impact Assessment (LCIA). In this phase the impacts from the system given the functional unit is calculated for the chosen impact categories, the method for calculating these impacts will be covered in this section, for a more thorough walkthrough see Nyhus 2013 [14, p. 14-19].

### 2.3.1 Stressors & Contribution Matrix

In LCA the emissions from the processes is called stressors. The stressor intensities $s$ are structured in a matrix where $n$ processes lies in the columns and the $m$ different stressor intensities are in the rows. The general matrix is shown in eq. (10). This matrix is made by collecting data from the different processes and must be per unit produced at the process.

$$\mathbf{S} = \begin{Bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ s_{m1} & s_{m3} & \cdots & s_{mn} \end{Bmatrix} \tag{10}$$

The total output of stressors from the whole system is structured in a vertical vector $\mathbf{e}$ for $m$ stressors, this is given by eq. (11).

$$\mathbf{e} = \mathbf{S}\mathbf{x} \tag{11}$$

To distinguish between the processes we use $\hat{\mathbf{x}}$ [2] instead of $\mathbf{x}$, this gives us a matrix $\mathbf{E}$ with $m$ stressors and $n$ processes, shown in eq. (12).

$$\mathbf{E} = \mathbf{S}\hat{\mathbf{x}} \tag{12}$$

To calculate how much contribution each stressor give to the different impact categories, a contribution matrix $\mathbf{C}$ is needed. This matrix contains the contribution factor of each stressor connected to every impact category. This matrix is usually pre-made and is embedded in the LCA software, see Nyhus 2013 [14, p. 20-26] on how these are calculated for the Recipe-method.

[2] $\hat{\mathbf{x}}$ is the matrix with the vector $\mathbf{x}$ on the diagonal and zeroes elsewhere.

### 2.3.2 Impact Vector & Matrix

The impact vector $\mathbf{d}$ contains the total impacts for every category and is defined in eq. (13).

$$\mathbf{d} = \mathbf{C}\boldsymbol{e} \tag{13}$$

The impacts stemming from each process is found in the process impact matrix $\mathbf{D}_{\text{pro}}$, defined in eq. (14).

$$\mathbf{D}_{\text{pro}} = \mathbf{C}\mathbf{E} \tag{14}$$

The impacts stemming from each stressor is found in the stressor impact matrix $\mathbf{D}_{\text{str}}$, defined in eq. (15)[3].

$$\mathbf{D}_{\text{str}} = \mathbf{C}\hat{\boldsymbol{e}} \tag{15}$$

### 2.3.3 Foreground & Background Modeling

When modelling a system for an LCA we divide the system into a foreground and a background. The foreground is the system of processes within the system boundary, while the background is everything on the outside of the system boundary. Data from the background is usually collected from a database such as Ecoinvent. The requirement matrix $\mathbf{A}$ is then structured as seen in eq. (16). $\mathbf{A}_{\text{ff}}$ is the foreground to foreground requirements, $\mathbf{A}_{\text{fb}}$ is the foreground to background requirements, $\mathbf{A}_{\text{bf}}$ is the background to foreground requirements, and $\mathbf{A}_{\text{bb}}$ is the background to background requirements. Similarly the other vectors and matrices also must be structured the same way.

$$\mathbf{A} = \begin{Bmatrix} \mathbf{A}_{\text{ff}} & \mathbf{A}_{\text{fb}} \\ \mathbf{A}_{\text{bf}} & \mathbf{A}_{\text{bb}} \end{Bmatrix} \tag{16}$$

### 2.3.4 Allocated Impacts

It isn't enough to just find the total impacts from the systems, it's also a need to find the impacts that is attributed to the foreground processes. $\mathbf{D}_{\text{pro}}$ includes both the foreground

[3] $\hat{\boldsymbol{e}}$ is the matrix with the vector $\boldsymbol{e}$ on the diagonal and zeros elsewhere.

and background processes and doesn't show how much impact from the background processes is instigated in the foreground processes. $\mathbf{D}_{pro,f}$ on the other hand contains the total impacts from the system divided on the foreground processes only, this gives us a better picture of the real impacts a process really creates. $\mathbf{D}_{pro,f}$ is the sum of the indirect impacts created in the background processes due to the demand from the foreground processes $\mathbf{D}_{pro,bf}$, and the direct impacts from the foreground processes themselves $\mathbf{D}_{pro,ff}$, see eq. (17). See Nyhus 2013 [14, p. 17] for how this is calculated.

$$\mathbf{D}_{pro,f} = \mathbf{D}_{pro,bf} + \mathbf{D}_{pro,ff} \tag{17}$$

### 2.3.5 Allocation

Allocation is the way LCA deals with processes that produce more than one valuable product, to find how much of the impacts stems from each of the products. The allocation method for this study is the substitution method, this is recommended by the ISO. It works by expanding the system to include additional products that is comparable to the co-products that needs allocation. The system boundary is moved such that the alternative products of the same kind is included in the foreground system. The impacts stemming from these alternative products are then subtracted from the total impacts of the process in question, and the rest of the impacts is then charged on the main product.

The main product, i.e. the product we want to determine the impacts of is $i = 1$, and $i \neq 1$ are the other products. The total impacts from a process with $n$ products is then given by eq. (18) [14, p. 19].

$$d = u_1 y_1 + \sum_2^n u_i y_i \tag{18}$$

Then the unit based impacts $u_i$ from the $n$ processes, is substituted by the unit based impacts $u_i^*$ from the product from the alternative process. We must assume that $u_i = u_i^*$, such that the total impacts is given by eq. (19).

$$d = u_1 y_1 + \sum_2^n u_i^* y_i \tag{19}$$

It follows then that the unit based impacts from the main co-product is given by (20).

$$u_1 = \left(d - \sum_2^n u_i^* y_i\right) y_i^{-1} \tag{20}$$

The two alternative methods of allocation is covered in Nyhus 2013 [14].

## 2.4 Life Cycle Interpretation

In the last phase of the LCA the results from the LCIA is interpreted and a conclusion is drawn. Evaluations of data completeness, sensitivity and consistency, issues in the former phases is done in this phase. The results is presented and conclusions and recommendations is given. See Nyhus 2013 [14, p. 27] [18].

# Part II

# LCA

# 3 Goal and Scope

In this section the goal and the scope of the study is chosen, we will chose what methodology to use, i.e. functional unit, impact assessment method, background database, system boundary and impact categories.

## 3.1 Goal

The goal of the study is as stated in the introduction, to compare a closed cage aquaculture system with an open cage system. The goal is to highlight differences in environmental impacts and to find spots in the production that contribute the most to environmental impacts. The closed system that will be used as reference is a fish farm in Brønnøysund, where a new concept design for closed sea cages is being developed. This system is described in section 1.

As pointed out in the introduction the key differences in the design compared with the open system are use of a bag in stead of a net to enclose the fish, the use of power for pumping water into the bag, and use of oxygen or production of oxygen for oxygenating the water inside the bag. Another big change is that both dead fish and sediments gets pumped to the surface, meaning lesser local emissions of waste. If there is a difference in the smolt phase, e.g. if the closed system have less mortality in the early life stage, it should be investigated seeing that the smolt phase is a energy heavy phase of the production, and making it more effective would surely decrease the impacts. In this study the smolt phase is identical for both systems.

## 3.2 Scope

### 3.2.1 System Boundary

Since this is a comparative study will the focus of the study be on comparing the two systems, and not on the absolute values of the results. Both the closed and the open system have the same system boundary, see figure 5. The main processes included are smolt production, feed production and the fish farm. The infrastructure construction process is to be neglected due to low impacts stemming from the phase in similar studies, see Nyhus 2013 [14, p. 32] for more on this. As seen in the figure, the system boundary is at farm gate, which is the most commonly used system boundary, see Nyhus 2013 [14, p. 32]. By doing this we don't need to model the processes like slaughtering and transport to market, seeing that those processes are identical for both the closed and open system. We also don't need use allocation on the fish in this case when the fish is still in one piece and is seen as one product. Had we had the system boundary at market we would have had to allocate the different co-products of the fish, e.g. the fillet and the guts. This was similarly done by Groenros et al. 2006 [19], avoiding allocation by using ungutted fish as functional unit. Allocation might be needed when dealing with the waste collected from the fish farm. If the sediments from the fish cage can be used as say for example fertilizer, we may use system expansion to exclude the impacts from the production of the same amount of fertilizer from the study, see section 2.3.4 on allocation for how this is done. Though for the main analysis allocation is not needed, since the waste won't be treated as a product.

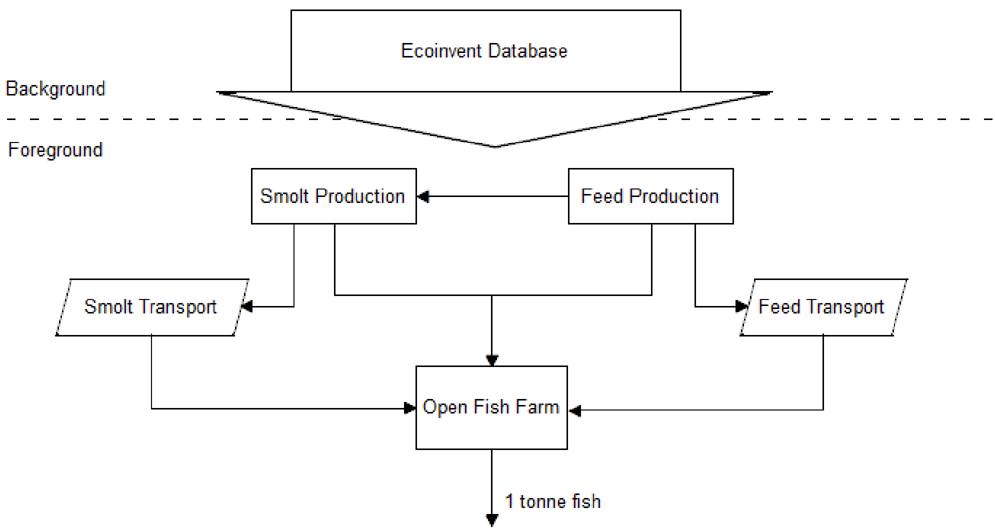


Figure 5: system boundary used in the study

### 3.2.2 Functional Unit

Seeing that the system boundary is at farm gate, a functional unit of 1 tonne of live fish is appropriate. This was used in 6 of 11 studies reviewed in the literature review done by Nyhus 2013 [14, p. 28]. Choosing a commonly used functional unit makes it easier to compare the results with similar studies, 1 tonne is also easy to scale.

### 3.2.3 Software and Background Database

The choice of LCA software is one of preference more than a methodological choice. Simapro is by far the most used LCA software, but that does not mean it's better than any other software, the cogs running in the background of the software are the same. Professor Anders Strømman recommended using the internally developed LCA software Arda. Arda uses the ReCiPe method and has the Ecoinvent database integrated. Ecoinvent is regarded as the best background database for European use [15]. It contains data on energy supply, fuels, materials, transport etc. Arda can also choose what characterization perspective to use, see Nyhus 2013 [14, p. 32].

The impact categories that will be included are all categories from the ReCiPe method, see section 2.1.2 on what categories that are included. Focus will be on climate change, toxicity, acidification and eutrophication.

# 4 Life Cycle Inventory

The LCA is carried out using data from various sources in the Norwegian fish farming industry. Communication with the different actors is done by phone interviews, e-mails and personal meetings. The data collected is for the most part input requirements calculated by the actors themselves. Direct emissions is for the most part calculated from the input data. Construction and demolition data for the farms, smolt and feed production facilities is neglected in this LCA due to time and resource constrictions. This is supported by the literature review, Nyhus 2013 [14, p. 29], as it's found to have negligible effect on the outcome of the LCA. This section covers the inventory modelling of the different processes. Full inventories is found in Appendix A.

## 4.1 System Models

This LCA is a comparative LCA [14, p. 5], therefore we have to model both systems in a way that makes comparison possible. In this LCA the open system is used as a baseline from which the closed system is modelled, it means that it's assumed that the closed system have the same base requirements as the open system. This assumption is founded on the closed fish farm having the same location and basic systems like workers, feeding system, work vessel etc., as the open fish farm. This might not be totally accurate since one of the most appealing aspects of the closed fish farm is that it can be placed on locations that open fish farms cannot due to environmental factors like current, topography etc. Such as placing a closed fish farm in a sound with little to no current as long as water can be collected from sufficient depth. This will likely make the base requirements for the closed farm lower than a similarly sized farm that is placed on a regular farming site, but it is still to be shown, and therefore we need to assume same base requirements for the closed fish farm in this study. The parameters exclusive of the closed system have the prefix 'added' to easier differentiate between the requirements.

### 4.1.1 Open System

Figure 6 shows the open fish farm system that is used as baseline in this LCA. Foreground processes includes the fish farm, feed and smolt production facilities, and feed and smolt transport. Background processes includes electricity, fossil fuels, oxygen production, agricultural ingredients; all collected from the Ecoinvent database. Background data on the fish content in the feed is not found in Ecoinvent and have to be collected from an earlier study [20], the same had to be done for the feed ingredient wheat gluten [21]. Emissions is not shown in the flowchart but is included in the LCA, stressor inventories is made by manual calculation based on the requirements, emission factors for the different fuels is collected from the 'United States Environmental Protection Agency' website [22] [23] [24], the different stressor contributions is collected from the Ecoinvent database.

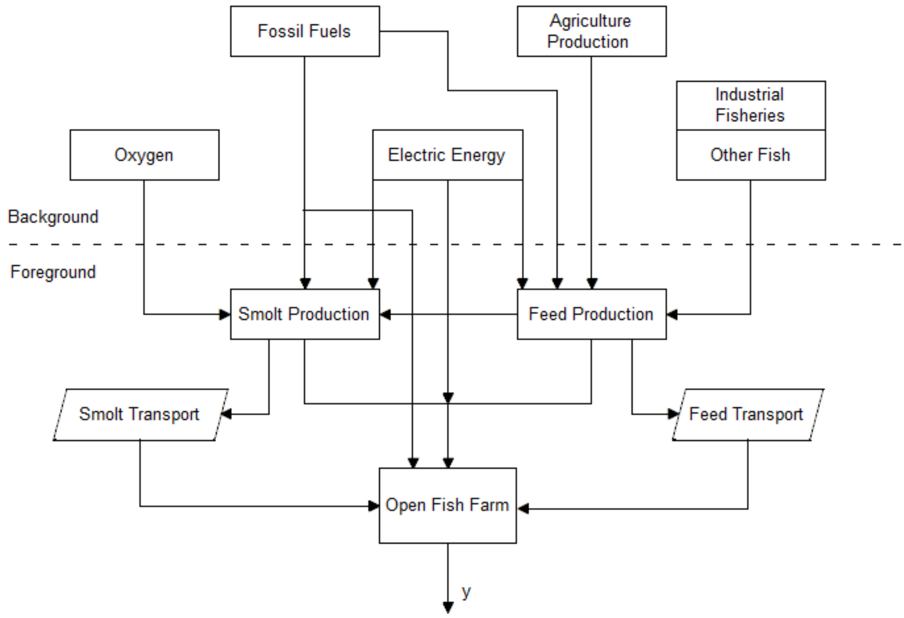


Figure 6: Flowchart showing the background and foreground flow for the open fish farming system

Data for the open system is collected from large actors including, Marine Harvest, Sinkaberg Hansen, Skretting, Biomar and Ewos. Contact is conducted for the most part by telephone, and continued by e-mail. Feed factor for the open system is 1.10.

Data on the smolt production is collected from Marine Harvest and Sinkaberg Hansen; and included feed, electricity, oxygen and fossil fuels requirements; an average of the two is used in the LCIA. Data on the feed production is collected from Skretting and supplemented with data from Biomar and Ewos, we'll come back to the feed model below. Data on the open fish farm is collected from Marine Harvest via email; and included feed, electricity and fossil fuel requirements. Medication inventories is not covered in this study due to lack of reliable data. Nutrient emissions from the fish faeces is included, but is restricted to nitrogen, phosphorus and inorganic compounds.

### 4.1.2 Feed Modeling

Of the data collected from the feed producers we compile a feed composition, seen in table 1. Ingredients like fish meal and oil have steadily been decreasing the last few years and has been replaced by agricultural alternatives, this will probably have a positive effect on the impacts. Other requirements is covered in the full inventory that is in Appendix A. We see that the fish content in the form of fish meal and fish oil is quite low compared to what have earlier been used in fish feed, e.g. Ellingsen et al. 2006, which used a modelled fish feed with 35% fish meal, 5% from ensilage, and 28% fish oil. The industrial fisheries is already reached their limit on how much biomass they can get from the ocean. The fish farming industry must therefore decrease the fish input in the feed to be able to grow [25], results from earlier studies must for that reason be treated in context with this.

Table 1: List of ingredients used in feed model given in percentage of produced weight.

| Feed Ingredients | |
|---|---|
| **Marine Protein** | |
| Fish meal | 15% |
| Fish Meal from by-products | 2% |
| | 17% |
| **Marine Oils** | |
| Fish oil | 11.5% |
| | 11.5% |
| **Agricultural Proteins** | |
| Soy Concentrate | 25% |
| Fava Beans | 5% |
| Wheat Gluten | 5% |
| Rape Meal | 5% |
| | 40% |
| **Agricultural Oils** | |
| Rapeseed Oil | 19% |
| | 19% |
| **Carbohydrates** | |
| Wheat | 12.5% |
| | 12.5% |
| **Total Sum** | 100% |

### 4.1.3 Closed System

In figure 7 we can see that the basis for the closed system is the same as for the open system, the difference being the added requirements as marked with dotted lines. Oxygen in liquid form is added to the closed fish cage to oxygenate the water for better fish growth. The added electricity is from the different pumps that runs the closed fish cage, this includes two pumps of 2.5 kW pumps water into the fish cage, these is running continuous all the time; one pump of 0.55 kW on 85 % load for sludge removal, that is also running continuously; and one pump of 1.5 kW that runs three minutes a day. All figures is for one cage. The feed factor for the closed system is approximately 1.25 for the pilot project, this figure have very high uncertainty, and that must be accounted for in the LCIA. The closed system is expected to have similar feed factor as open systems [26], we are therefore looking at a spectre of feed factors in this LCA. For the calculations we assume a production period of 16 month from the time smolt is placed in the fish cage until delivery to the well boat, and each cage is assumed to have a yearly production of 250 tonne live fish. Complete inventory and calculations can be found in Appendix A. Oxygen is calculated with a requirement of 0.55 kg per kg of fish. For the pilot project oxygen was bought in tanks. The concept of the closed farm system is however thought to use oxygen produced at farm site, and this will therefore be the main way oxygen is modelled in this LCA. After discussion with Akvafuture and research of oxygen manufacturers a requirement of one kWh per kg of oxygen produced is assumed [26].

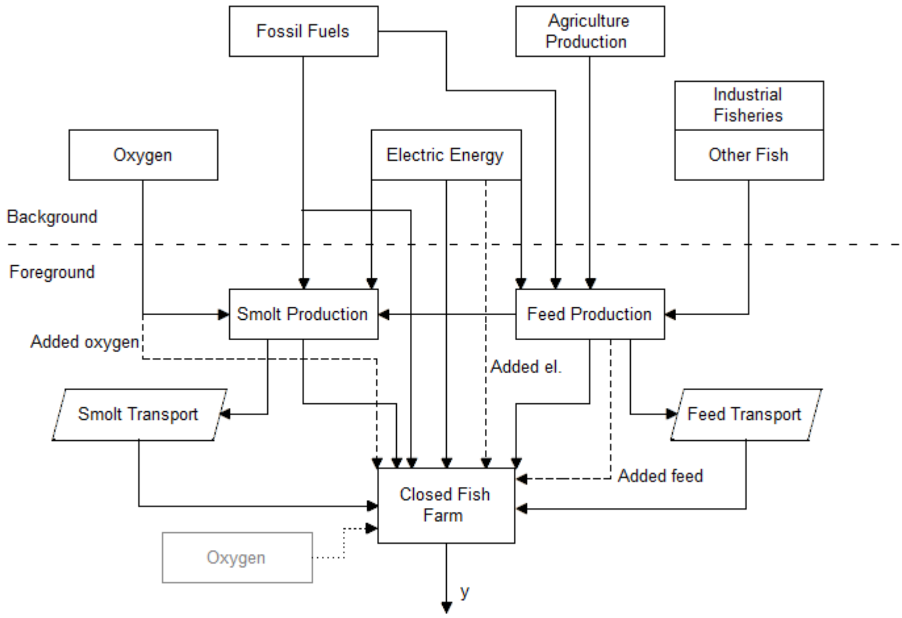


Figure 7: Flowchart showing the background and foreground flow for the closed fish farming system

### 4.1.4 Transportation

Figure 8 shows how transport of the smolt and feed is modelled. The dotted lines from the smolt and feed to the transport processes is the real flow, while the solid lines from the pre-modelled transport process to the foreground transport is the modelled flow, see 2.2.2 and Nyhus 2013 [14, p. 13].

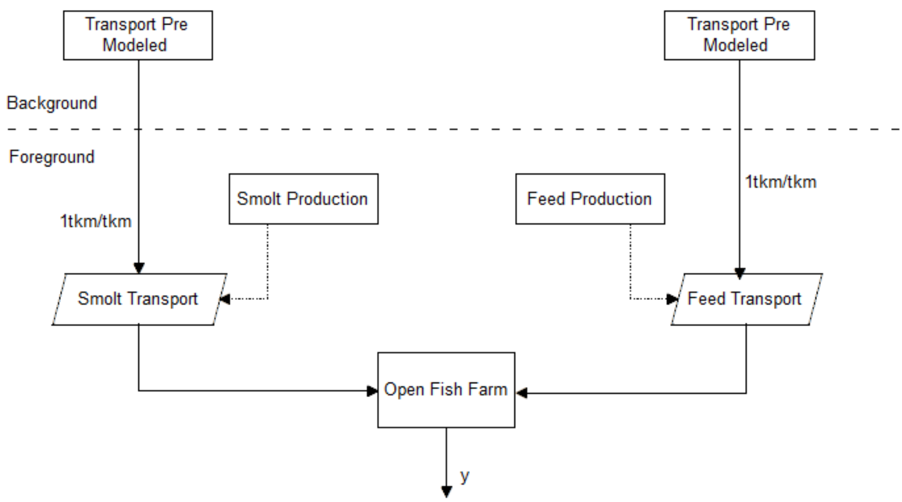


Figure 8: Flowchart showing the transport model

## 4.2 Inventory

Table 2 shows the background to foreground inventory for the two systems, given per unit output of the foreground process. This is the contents of the $\mathbf{A}_{\mathrm{bf}}$ matrix in list form. Table 3 on next page is the foreground to foreground inventory for the systems, the $\mathbf{A}_{\mathrm{ff}}$ matrix discussed in section 2.2. Full inventory is found in Appendix A.

Table 2: Inventory of the background to foreground

| Background Name | Foreground Process Name | Amount | Unit |
|---|---|---|---|
| Electricity | Open Fish Farm | 26,00 | kWh |
| Diesel | Open Fish Farm | 25,19 | kg |
| Petrol | Open Fish Farm | 0,29 | kg |
| Electricity | Closed Fish Farm | 736,18 | kWh |
| Diesel | Closed Fish Farm | 22,34 | kg |
| Petrol | Closed Fish Farm | 0,29 | kg |
| Electricity | Smolt Production | 4230,00 | kWh |
| Diesel | Smolt Production | 127,50 | kg |
| Oxygen | Smolt Production | 500,00 | kg |
| Transport Ship | Smolt Transport | 1,00 | tkm |
| Electricity | Feed Production | 111,11 | kWh |
| Propane | Feed Production | 1,22 | kg |
| Diesel | Feed Production | 0,23 | kg |
| Natural gas | Feed Production | 11,58 | Nm3 |
| Soybean Meal | Feed Production | 250,00 | kg |
| Fave Beans | Feed Production | 50,00 | kg |
| Rape Meal | Feed Production | 50,00 | kg |
| Rape Oil | Feed Production | 190,00 | kg |
| Wheat Grains | Feed Production | 125,00 | kg |
| Fish Meal | Feed Production | 150,00 | kg |
| Fish Oil | Feed Production | 115,00 | kg |
| Fish Meal By-products | Feed Production | 20,00 | kg |
| Wheat Gluten | Feed Production | 50,00 | kg |
| Transport Ship | Feed Transport - ff | 1,00 | tkm |
| Transport Lorry | Feed Transport - sp | 1,00 | tkm |

Table 3: Inventory of the foreground to foreground, $\boldsymbol{A}_{\mathrm{ff}}$

| Full Name | Unit | OFF. | SP. | ST. | FP.0.95 | FP.1.10 | FP.1.25 | FT.0.95 | FT.1.10 | FT.1.25 | FTsp. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Open Fish Farm | t | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Smolt Production | t | 0,02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Smolt Transport | tkm | 2,3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (0.95) | t | 0,95 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (1.10) | t | 1,1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (1.25) | t | 1,25 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (0.95) | tkm | 760 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (1.10) | tkm | 880 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (1.25) | tkm | 1000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. sp | tkm | 0 | 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# 5 LCIA

The third part of the LCA is to do an life cycle impact assessment (LCIA) on the data from the LCI. The choices made in the LCIA and results of this analysis is presented in this section.

The LCIA is done in Arda for three reference feed factors at the fish farms themselves, 0.95, 1.10 and 1.25 kg feed per kg fish. This is done to cover a large spectre of different efficiencies at the farms, seeing that feed efficiency is different depending on the farm, and especially dependant on country where feed factor ranges all the way up to 1.49 [12]. Background resources is made as relevant as possible with special focus of choice of electricity mix. See Appendix A for the full inventories. Allocation is not needed in this study, seeing that we have no other products than the live fish at farm gate.

## 5.1 Electricity

As mentioned in the last section the oxygen is mainly modelled to be produced on the farm site, requiring one kWh per kg. This electricity is added to the other requirements of the closed system, and can therefore not be distinguished in the main results, a sensitivity analysis on the oxygen is done in next section.

The added electricity from the oxygen makes the results from the closed system sensitive to changes in environmental impacts from the electricity, this makes the choice of electricity mix (el-mix) from the background important since choosing one el-mix over the other significantly changes the results. See figure 13 for the results of the closed system at a feed factor of 1.10 using three different el-mixes, Norwegian (NO), Nordic production (NORDEL), and European production (RER). We see a 30% increase in GWP from using NO to RER. NORDEL is today outdated, but can be used for modelling purposes [27], and is added as a less optimistic reference. RER is added to put the results in an European perspective, and is not really realistic as el-mix in Norway.

The impacts from one kWh of electricity is showed in figures 9, 10, 11 and 12. The Norwegian el-mix is for the most part made out of hydro power (approx. 96%), NORDEL and European el-mix is comprised of a high part of fossil fuels, and have because of that significantly higher environmental impacts [27].

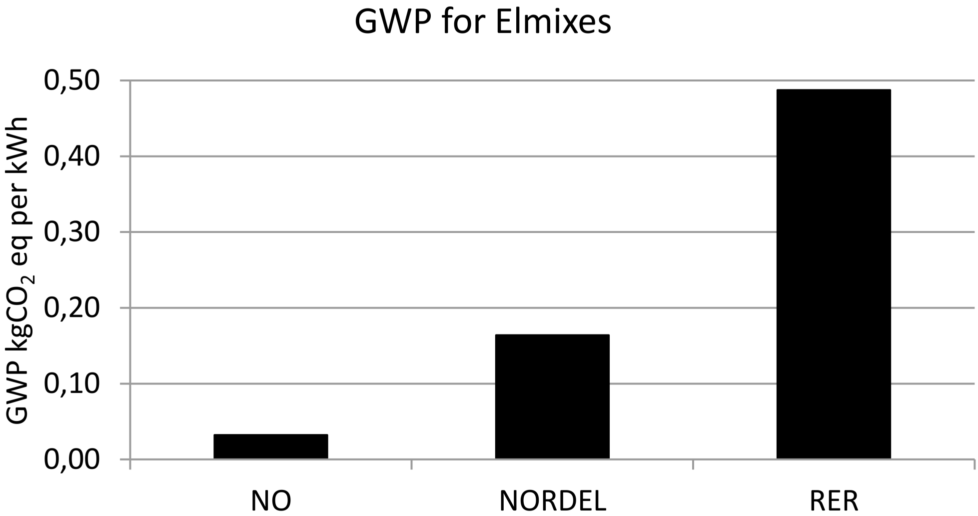


Figure 9: Global warming potential for three elmixes used in this LCA, Norwegian electricity mix (NO), Nordic electricity production mix (NORDEL), and European electricity production mix (RER).

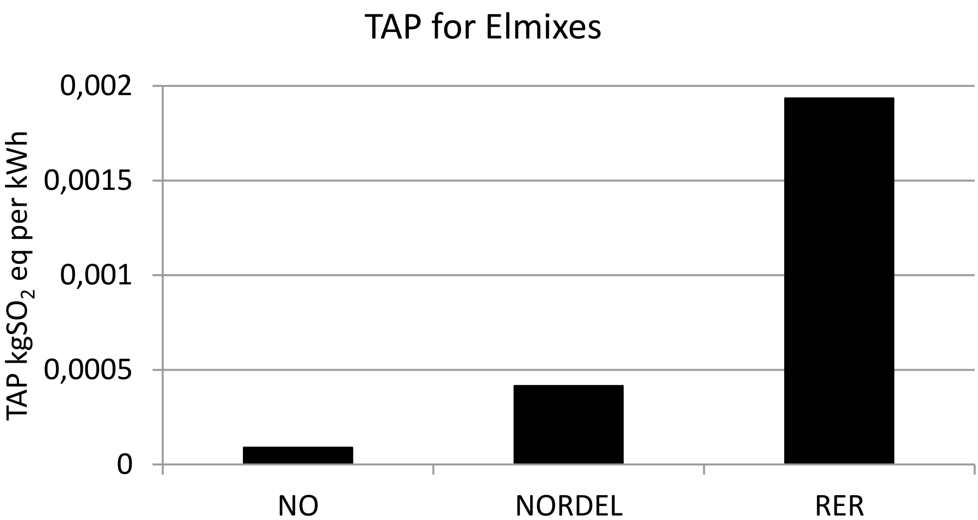


Figure 10: Terrestrial acidification potential for three elmixes used in this LCA, Norwegian electricity mix (NO), Nordic electricity production mix (NORDEL), and European electricity production mix (RER).

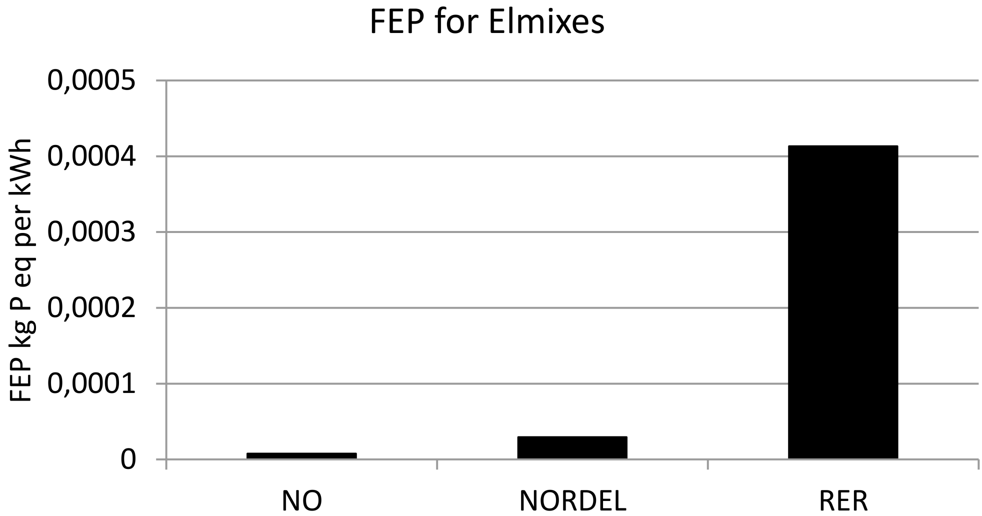


Figure 11: Freshwater eutrophication potential for three elmixes used in this LCA, Norwegian electricity mix (NO), Nordic electricity production mix (NORDEL), and European electricity production mix (RER).

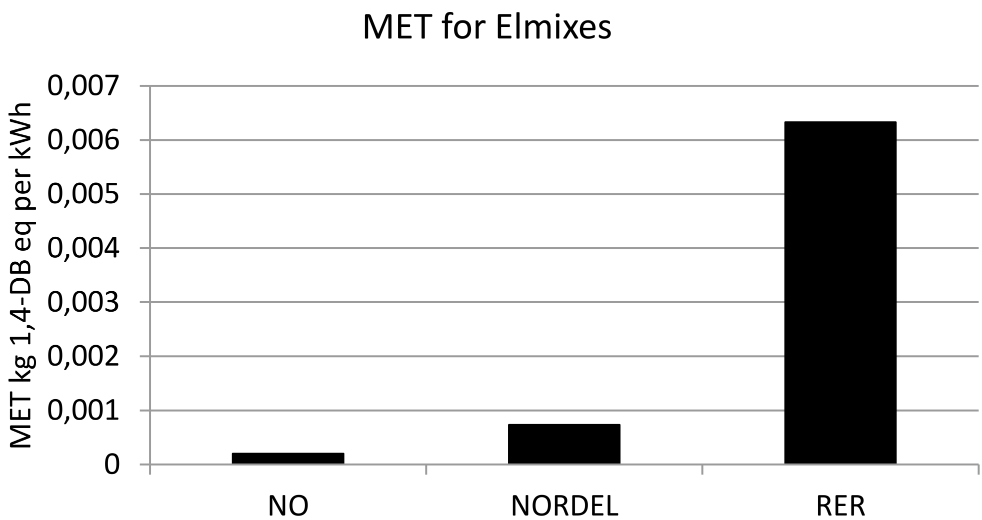


Figure 12: Marine ecotoxicity for three elmixes used in this LCA, Norwegian electricity mix (NO), Nordic electricity production mix (NORDEL), and European electricity production mix (RER).

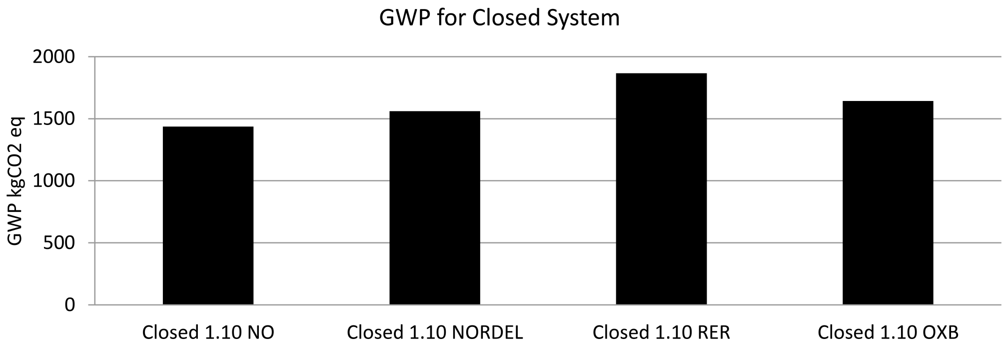


Figure 13: Global warming potential for the closed system, the three first producing oxygen at the farm site using the different el-mixes NO, NORDEL and RER; the last column is for oxygen required from background OXB.

We do one LCIA-run for the closed system at a feed factor of 1.10, where the oxygen is produced in the background system. We use a liquid oxygen with the European suffix RER, see Appendix A. The last column in figure 13 shows the impact from the closed fish farm at a feed factor of 1.10 compared to the same system producing oxygen at the farm site for the three el-mixes. We see that for a Norwegian el-mix there are about 200 kg higher impacts from buying oxygen versus producing it on the farm.

## 5.2 Impacts by Category

Table 4 shows the full impact vectors for the three feed factors and el-mixes.

Figure 14 shows the impacts for both open and closed systems with a feed factor of 1.10, using the three el-mixes. We see that for the NO el-mix the difference between the open and closed system is very little, with an increasing difference for GWP and TAP when the electric power gets dirtier. This suggests that FEP and MET is not sensitive to burning of fossil fuels, which is likely to be the cause of the difference in the two other categories.

Table 4: Results from LCIA of open and closed fish farm system.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SYS | Open | Open | Open | Open | Open | Open | Open | Open | Open | |
| | EM | NO | NORDEL | RER | NO | NORDEL | RER | NO | NORDEL | RER | |
| Category | FF | 0,95 | 0,95 | 0,95 | 1,10 | 1,10 | 1,10 | 1,25 | 1,25 | 1,25 | |
| GWP | | 1,25E+03 | 1,28E+03 | 1,35E+03 | 1,42E+03 | 1,46E+03 | 1,53E+03 | 1,60E+03 | 1,63E+03 | 1,71E+03 | |
| TAP | | 1,30E+01 | 1,31E+01 | 1,34E+01 | 1,47E+01 | 1,48E+01 | 1,52E+01 | 1,65E+01 | 1,65E+01 | 1,69E+01 | |
| FEP | | 2,16E+01 | 2,16E+01 | 2,16E+01 | 2,49E+01 | 2,49E+01 | 2,50E+01 | 2,82E+01 | 2,82E+01 | 2,83E+01 | |
| MET | | 1,66E+04 | 1,66E+04 | 1,66E+04 | 1,92E+04 | 1,92E+04 | 1,92E+04 | 2,18E+04 | 2,18E+04 | 2,18E+04 | |
| | SYS | Closed | Closed | Closed | Closed | Closed | Closed | Closed | Closed | Closed | ClosedOXB |
| | EM | NO | NORDEL | RER | NO | NORDEL | RER | NO | NORDEL | RER | NO |
| | FF | 0,95 | 0,95 | 0,95 | 1,10 | 1,10 | 1,10 | 1,25 | 1,25 | 1,25 | 1,10 |
| GWP | | 1,26E+03 | 1,38E+03 | 1,68E+03 | 1,44E+03 | 1,56E+03 | 1,87E+03 | 1,61E+03 | 1,74E+03 | 2,05E+03 | 1,64E+03 |
| TAP | | 1,29E+01 | 1,32E+01 | 1,46E+01 | 1,46E+01 | 1,49E+01 | 1,64E+01 | 1,64E+01 | 1,67E+01 | 1,81E+01 | 1,55E+01 |
| FEP | | 2,16E+01 | 2,16E+01 | 2,19E+01 | 2,49E+01 | 2,49E+01 | 2,53E+01 | 2,82E+01 | 2,83E+01 | 2,86E+01 | 2,51E+01 |
| MET | | 1,66E+04 | 1,66E+04 | 1,66E+04 | 1,92E+04 | 1,92E+04 | 1,92E+04 | 2,18E+04 | 2,18E+04 | 2,18E+04 | 1,92E+04 |

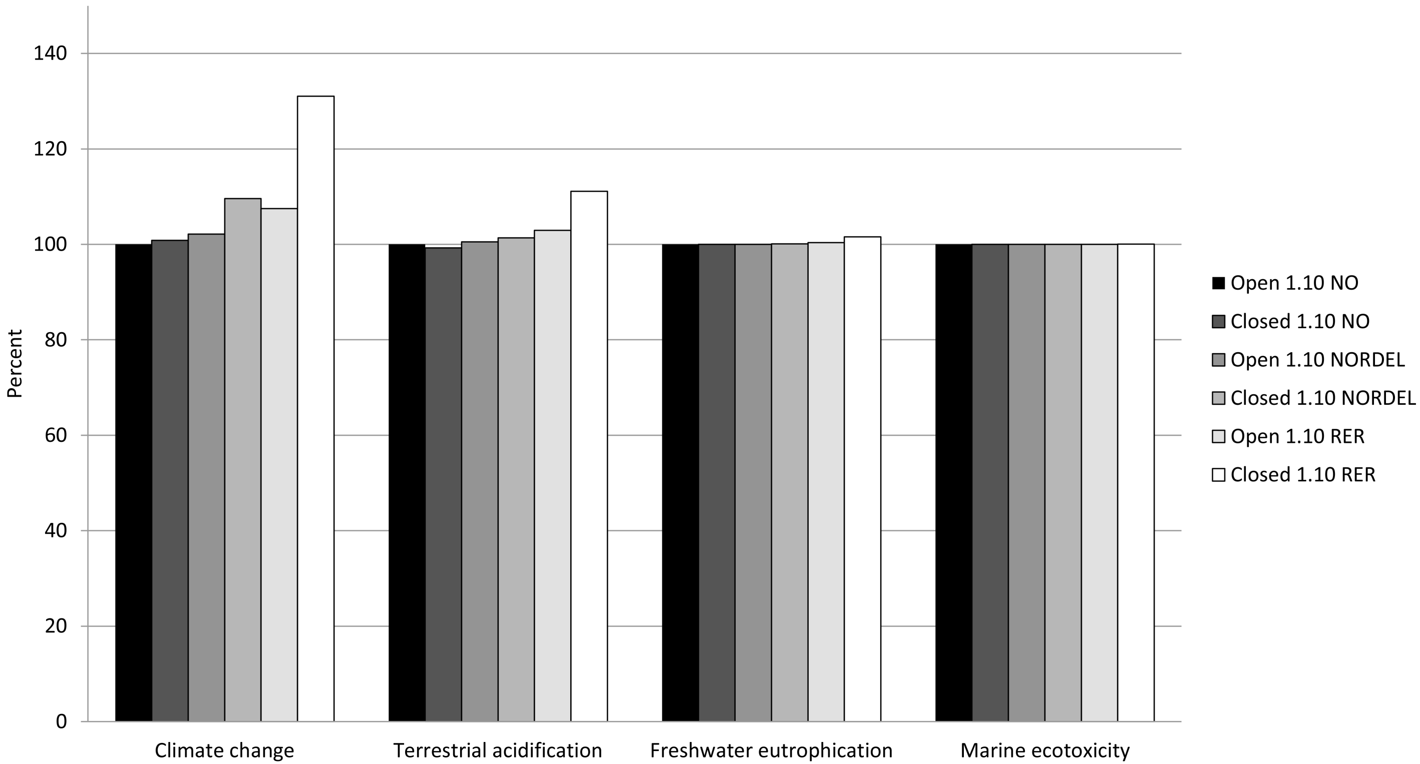


Figure 14: Impacts of the open and closed system using different elmix, relative to an open system (100%) using Norwegian electricity mix, all systems using feed factor 1.10 at farm.

Figure 15 shows the GWP from the open and the closed systems as a function of feed factor, graphs of all three el-mixes is included. Here we see the effect feed factor and choice of el-mix have on the climate change category. From the steepness of the graphs we see that the relative effect of feed factor doesn't change much from open to closed or from the cleanest to the dirtiest el-mix.

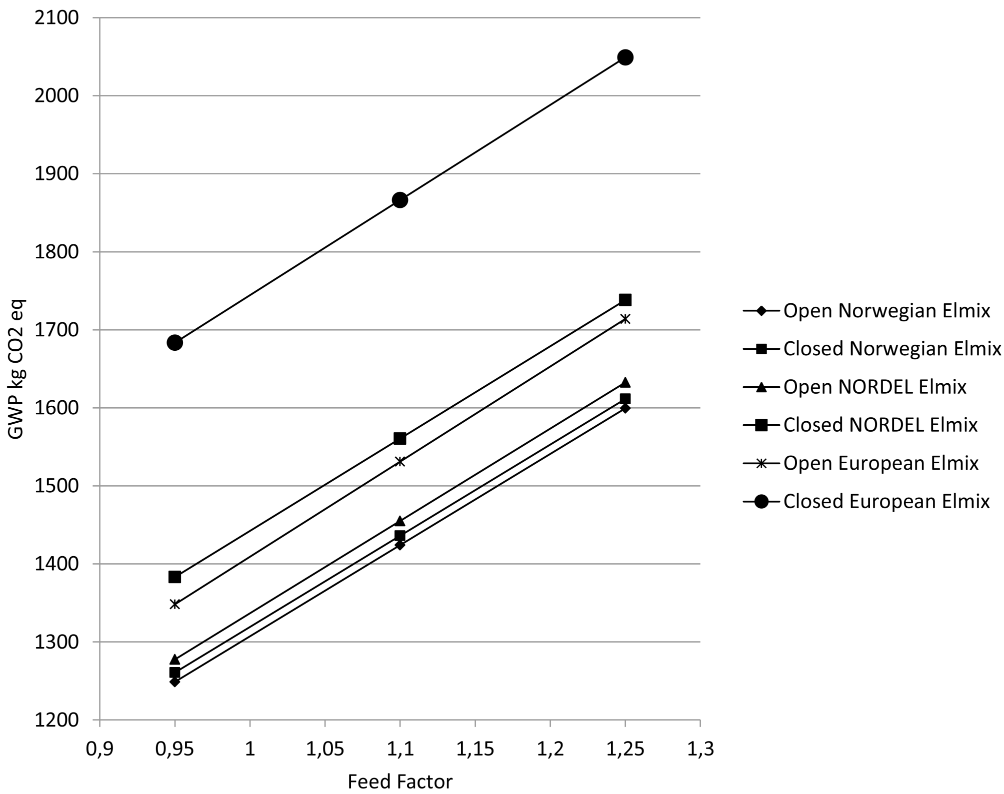


Figure 15: GWP of the open and closed system using different el-mix as a function of feed factor.

Figure 16 shows the same impacts as the graph above, and it illustrates the same results. We see that the difference between the open and the closed system is almost solely due to differences in el-mix impacts. The closed system is sensitive to change in el-mix due to high electricity requirements from the pumps and oxygen production at the closed fish farm. The closed farm system have a added electricity requirement that is six to seven times higher than for the open system. We do see a little jump when changing el-mix in the open system, this is due to electricity requirements in the feed and smolt production processes.

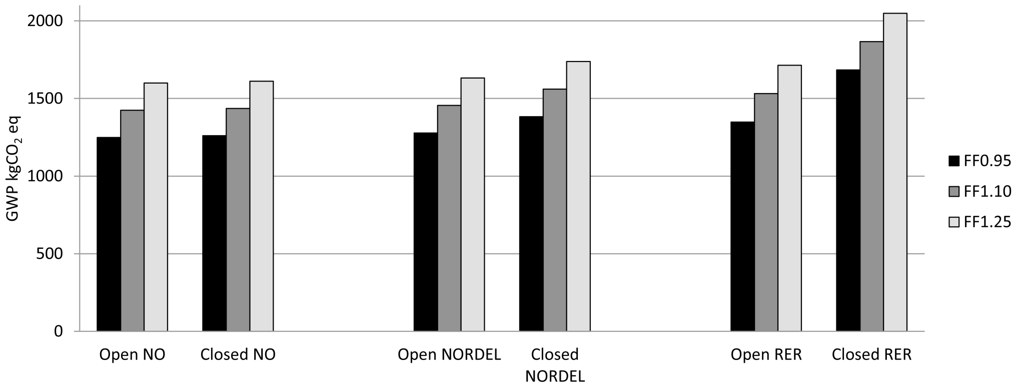


Figure 16: GWP of the open and closed system for the three el-mixes and feed factors.

Figure 17 shows the results of the terrestrial acidification category and paints the same picture as for GWP, the same observations stands for fig. 17 as for 16.

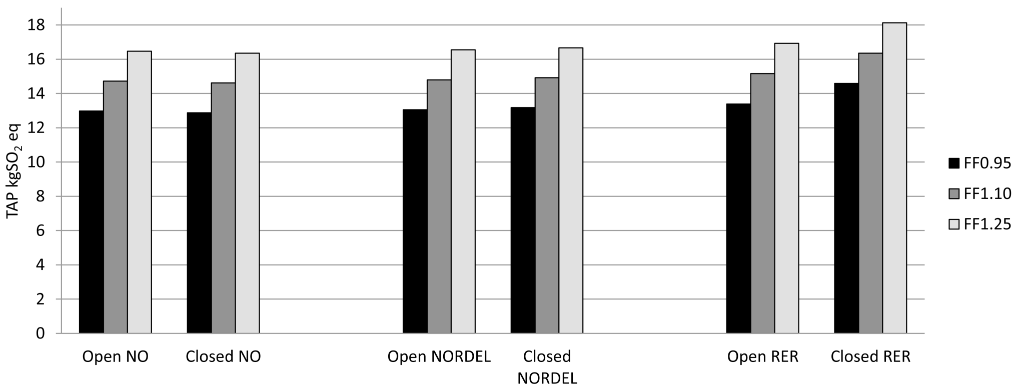


Figure 17: TAP of the open and closed system for the three el-mixes and feed factors.

Figure 18 shows the results of the freshwater eutrophication category. We see little difference from changing el-mix, and the same leap interval in impacts from feed factor change is seen for all three el-mixes. We see in figure 11 that even for RER the impacts from the electricity are really small compared to the impacts from the open system we use as base, e.g. a thousand kWh of added electricity will only contribute 0.4 kg P-equivalents.

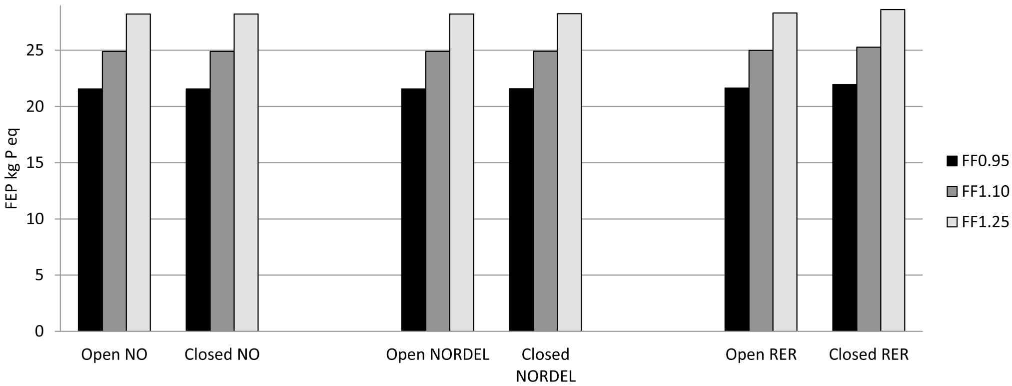


Figure 18: FEP of the open and closed system for the three el-mixes and feed factors.

Figure 19 shows the results of the marine ecotoxicity category. Here even more than for FEP the impacts from electricity production is so small it makes no difference on the results.

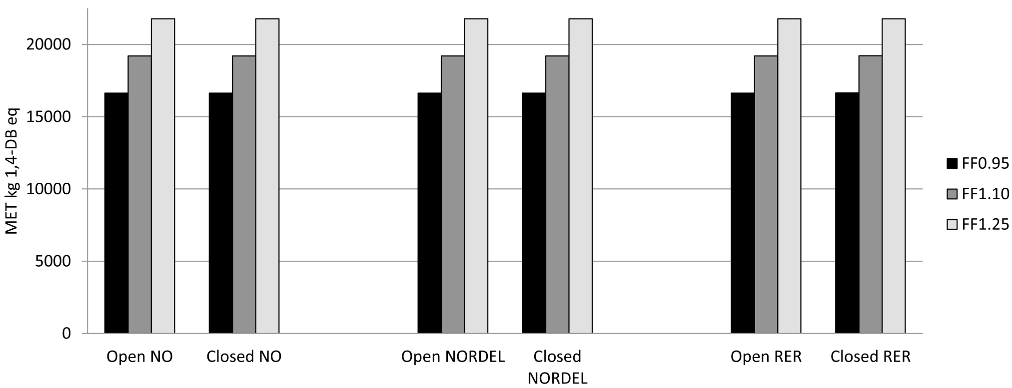


Figure 19: MET of the open and closed system for the three el-mixes and feed factors.

The consistent jump in impacts from the increase in feed factor will be covered in the next subsection.

# 6 Interpretation

In this section we are performing a contribution analysis to finding the relative impacts of the foreground processes; we are analysing the results to find the point of feed factor intersection where the open and the closed farm have the same impact; we are discussing data quality; and lastly we are further looking at parameter sensitivity.

## 6.1 Contribution Analysis, El-mix

On next page we see the relative impacts from the different foreground processes. The stack show the impact in percent relative to 100% of the total impacts in the category, i.e. both the direct and indirect impacts of the processes. The diagrams in figure 20 are chosen to illustrate the change in relative impacts that is due to change of el-mix. The European el-mix is chosen to best illustrate what happens when the impacts from electricity changes. Feed factor is held constant at 0.95.

We see in two diagrams on the top that there are little to no change in composition for FEP and MET, as earlier illustrated in figure 18 and 19. The feed process is totally dominating the categories, and a change in feed factor will change the impacts for the categories in a ratio one to one. For GWP and TAP we see that the electricity heavy smolt production process takes up more of the impacts when the el-mix changes.

We see in the two diagrams at the bottom that the same is true for FEP and MET as mentioned above, there are little difference in composition going from Norwegian to European el-mix, only a couple percent points increase for the closed fish farm due to the increased electricity requirement. We see a 7% point increase for TAP and a 17% point increase in GWP for the closed fish farm when switching el-mix. This shows how sensitive the closed system is to the choice of el-mix, and maybe especially if the technology is to be implemented in other countries with less clean el-mix than Norway.

The two transportation processes have no impact on FEP and MET, but have a couple of percent contribution in GWP and TAP, and is not impacted from change in el-mix.

The complete collection of stacked bar charts is be found in appendix C.

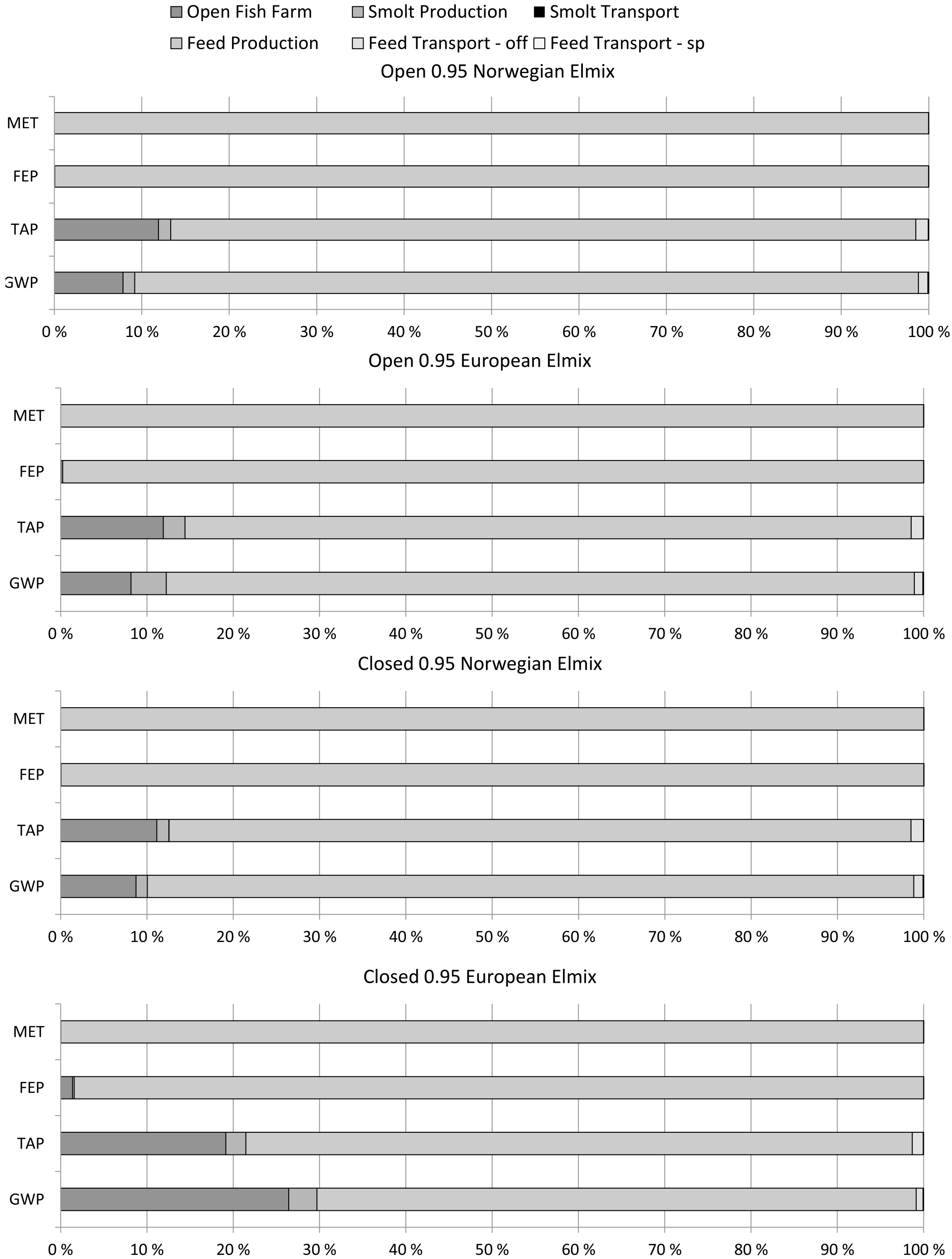


Figure 20: Relative impacts for the open system using NO and RER el-mix, for FF 0.95.

## 6.2 Contribution Analysis, Feed Factor

On next page we see the relative impacts from the different foreground processes. The stack show the impact in percent relative to 100% of the total impacts in the category, i.e. both the direct and indirect impacts of the processes. The diagrams in figure 21 are chosen to illustrate the change in relative impacts that is due to change in feed factor. Here we compare the open and closed systems using feed factors of 0.95 and 1.25, the two extremes is chosen to better illustrate what happens to the relative impacts of the foreground processes. Norwegian el-mix is used in all figures.

We see that for FEP and MET categories there are no change in relative impacts due to changes in system or feed factor. This is due to the high impacts from feed ingredients like crops and fish meal that goes into the feed production process. This means that a change in feed factor will increase the impacts from these categories in a ratio one to one.

For TAP and GWP we see only subtle changes between the open and the closed system of the same feed factor. The change in relative impacts for higher feed factor is obvious, seeing that it increases the requirements and the impacts from the feed production process.

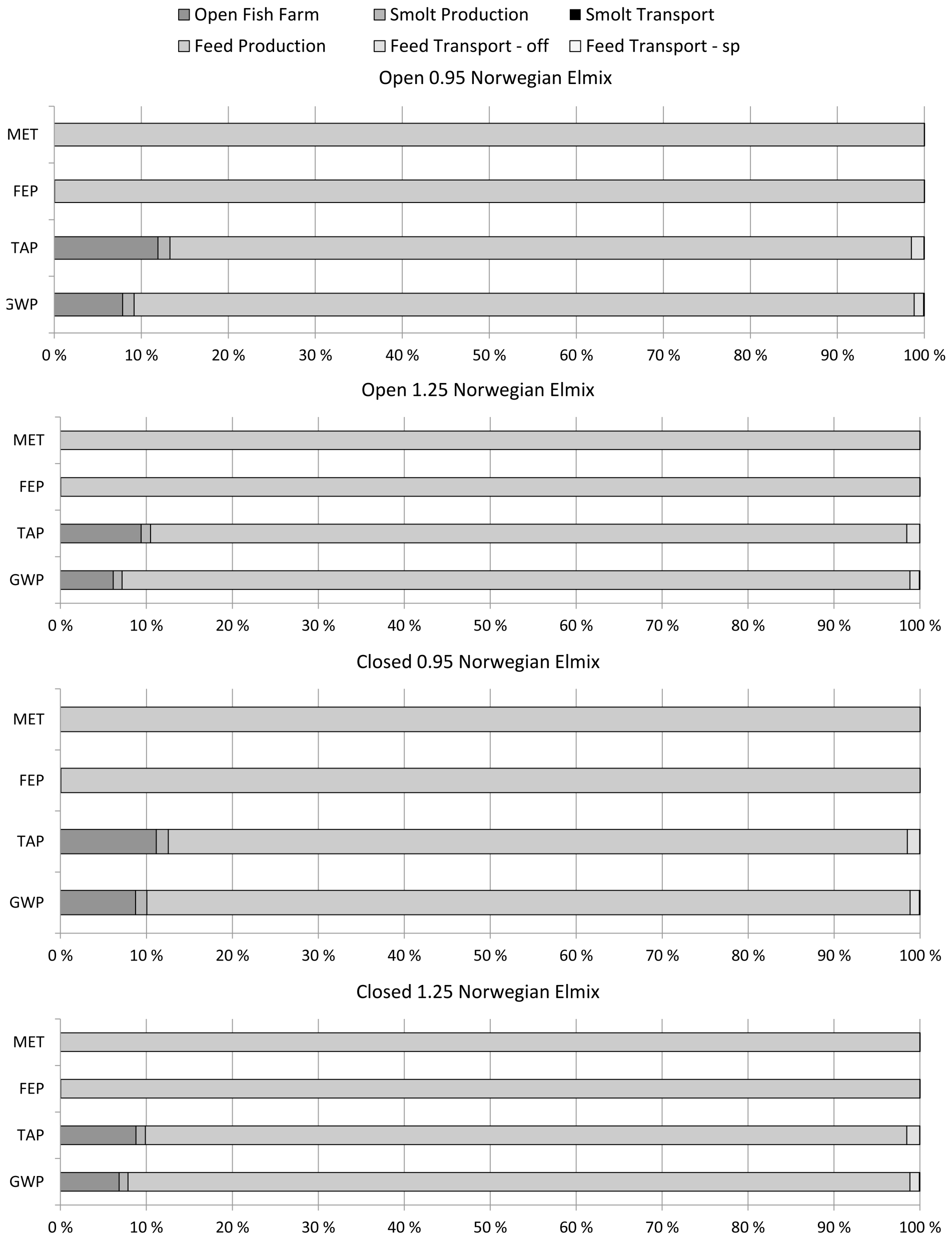


Figure 21: Relative impacts for the open and closed systems using NO el-mix, and FF 0.95 and 1.25.

## 6.3 Intersecting Impacts

Now we will see what feed factor the closed system must achieve to have the same GWP as an open system held at a constant feed factor. The open system GWP is held at the three feed factors 0.95, 1.10 and 1.25, while the closed system GWP is plotted as a function of the feed factor.

Figure 22 uses NO el-mix, and shows that the closed fish farm is just 0.01 of to have equal GWP as the open system. Figure 23 uses NORDEL el-mix, and shows that the feed factor of the closed system need to have a feed factor almost 0.15 lower to have equal GWP. Figure 24 uses RER el-mix, and illustrates the impossibility of attaining the same GWP for this el-mix, so long as the electricity requirements of the closed system is as high as it is.

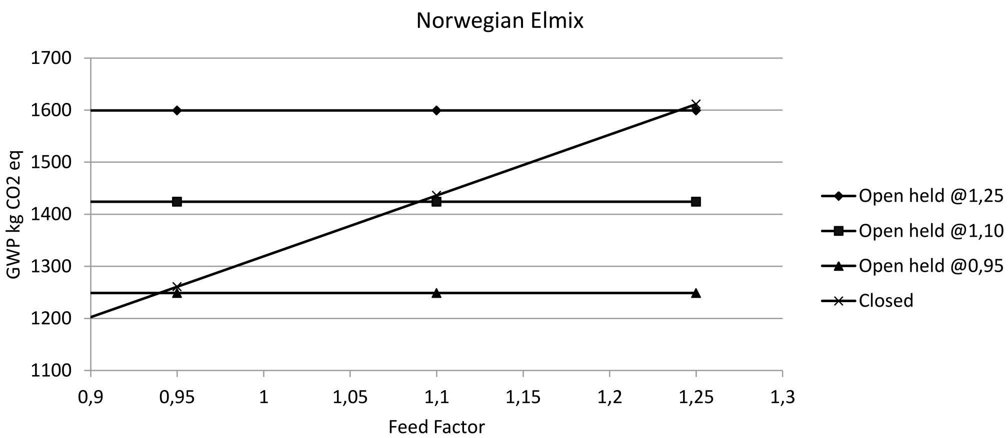


Figure 22: Points of intersection between open and closed system impacts, as a function of feed factor, NO el-mix.

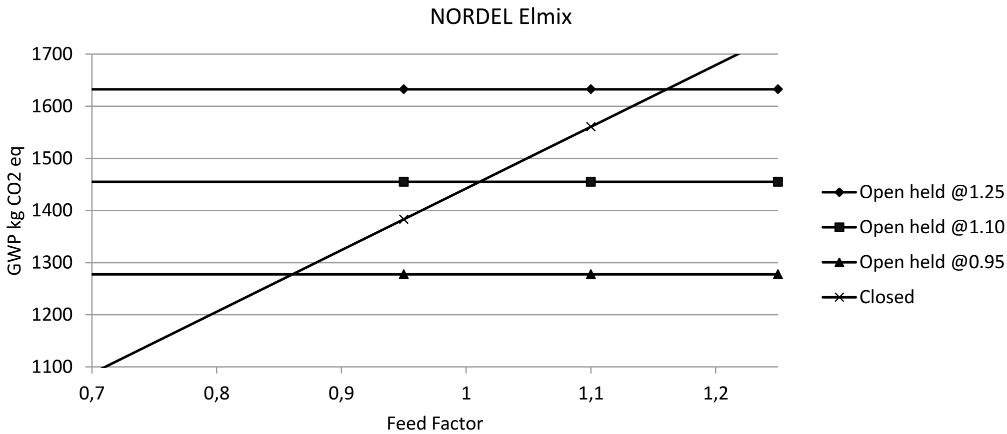


Figure 23: Points of intersection between open and closed system impacts, as a function of feed factor, NORDEL el-mix.

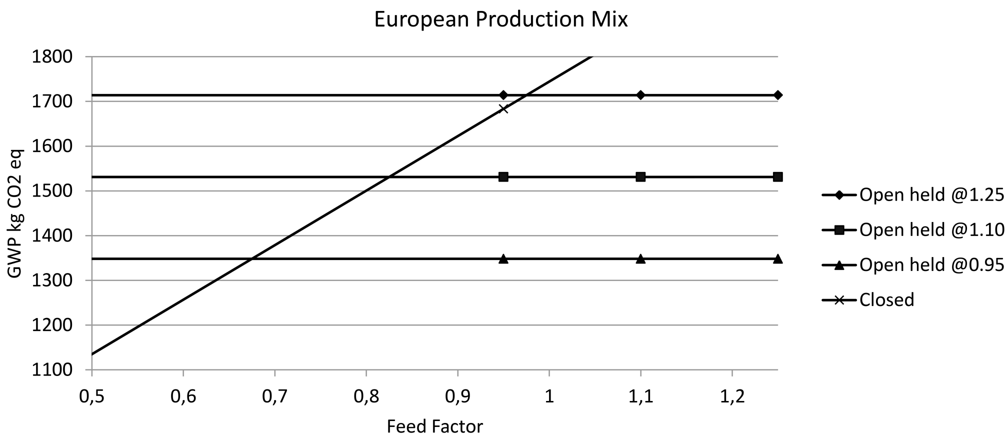


Figure 24: Points of intersection between open and closed system impacts, as a function of feed factor, RER el-mix.

## 6.4 Data Quality

The data for this study is collected by telephone and e-mail. The ISO states that the data quality should enable the goal and the scope of the study to be met [16]. We will in this section discuss the quality of the data used in this study.

The data is collected from multiple sources, which decreases likelihood of erroneous data, seeing that it is expected to be similarity between data sources, and should one data be way of the other it is checked for correctness. All data is recent, with the oldest being from 2012. This is important due to the rapid development of the industry, e.g. using old feed compositions would put too much weight on the fish ingredients of the fish feed. All data is from the Norwegian fish farming industry, making the results only viable in Norway.

As discussed in the sections above and in the next section, the most sensitive process was feed production, precision of the data collected from the process is therefore important. In the case of this study the data from the feed process have the highest quality of all the data collected. It was already compiled, checked and published [25].

The data from the open fish farm and the smolt production is of the lowest quality in this study. The data was collected by mail, and was in the form of company averages. This is ok since the sensitivity of the data is so low, meaning that a large error in the data from these processes would not shift the results of the LCIA. This is also supported by the fact that the data also was used in the closed system, and the difference of the two systems would only shift a little. The data from the closed system is also quite uncertain, and will also probably change as the technology matures. The same as for the open farm and the smolt production is true for the closed system.

The data is not exhaustively collected, meaning that only the most important requirements from the foreground processes is included. E.g. requirements and emissions from the construction and demolition of the fish farm, smolt production plant, oxygen production equipment and feed production plant is all excluded from this study. The results from this study can therefore not be used in an absolute sense, i.e. it cannot be directly compared to other studies with exhaustive inventories. The background database used is now outdated, but this version is consistent with many earlier studies, see Nyhus 2013 literature review Appendix D.

The lack of background data on fish meal and oil is the weakest part of the study, and inhibits the results from the other categories in Recipe to be used. Since the goal of the study was to compare the open and the closed system this can be tolerated; since the most important categories is to a acceptable degree covered, i.e. climate change, acidification, eutrophication and ecotoxicity.

## 6.5 Parameter Sensitivity

Parameter sensitivity have been a throughout theme for the results, and here we will look at the sensitivity for the three most contributing parameters for the closed system. This is done to determine how important the data quality for the given parameter is, seeing that a highly sensitive parameter need a high quality data to give an accurate result. The parameters we will look at is electricity excluding the oxygen production, oxygen production, and feed factor. We set up the LCIA to find the impacts increase in percent when we increase the requirements of the parameter in question. When running the analysis for the electricity and oxygen parameter we use a feed factor of 1.10, and we do runs for all three el-mixes.

The top three graphs in figure 25 shows the sensitivity for the GWP. On the left we see that an 25% increase in electricity on the closed fish farm, that is excluding requirements from oxygen production, will increase the GWP for the system in little degree. For the NO el-mix as little as 0.15% is seen, even for the RER el-mix no more than 1.25% increase is seen. This means that the data quality for the base electric requirements from the closed farm, e.g. power to the pumps and feeding system, is not critical to get a usable result. The middle graph show the increase in GWP when the farm or production requirements increase or decrease. We see that the oxygen is more sensitive than the base electric requirement, this is expected seeing that the requirements from the oxygen is larger than the rest of the farm requirements together. We see that even from the rather large oxygen production requirements there are little increase in GWP when using the NO el-mix. For the RER el-mix we are starting to see a more significant increase in GWP. This means that the data quality for the oxygen starts to become relevant as the el-mix becomes dirtier. On the right we see the increase in impacts from the change in feed factor. As expected the feed factor is the most sensitive of the parameters, and is therefore the most critical to get correct when collecting data and when interpreting the results. Different from the two other graphs we see that here the NO el-mix is the one that is the most sensitive with 22.5%, that is because of it having a larger relative share of the impacts than the RER and NORDEL el-mix, see figure 20. The feed production and requirement from the closed farm is therefore the most critical to get right when modelling and collecting data.

The bottom three graphs in figure 26 shows the sensitivity for the TAP. We see the same pattern is true for TAP as for GWP, the same arguments as mentioned above therefore stands.

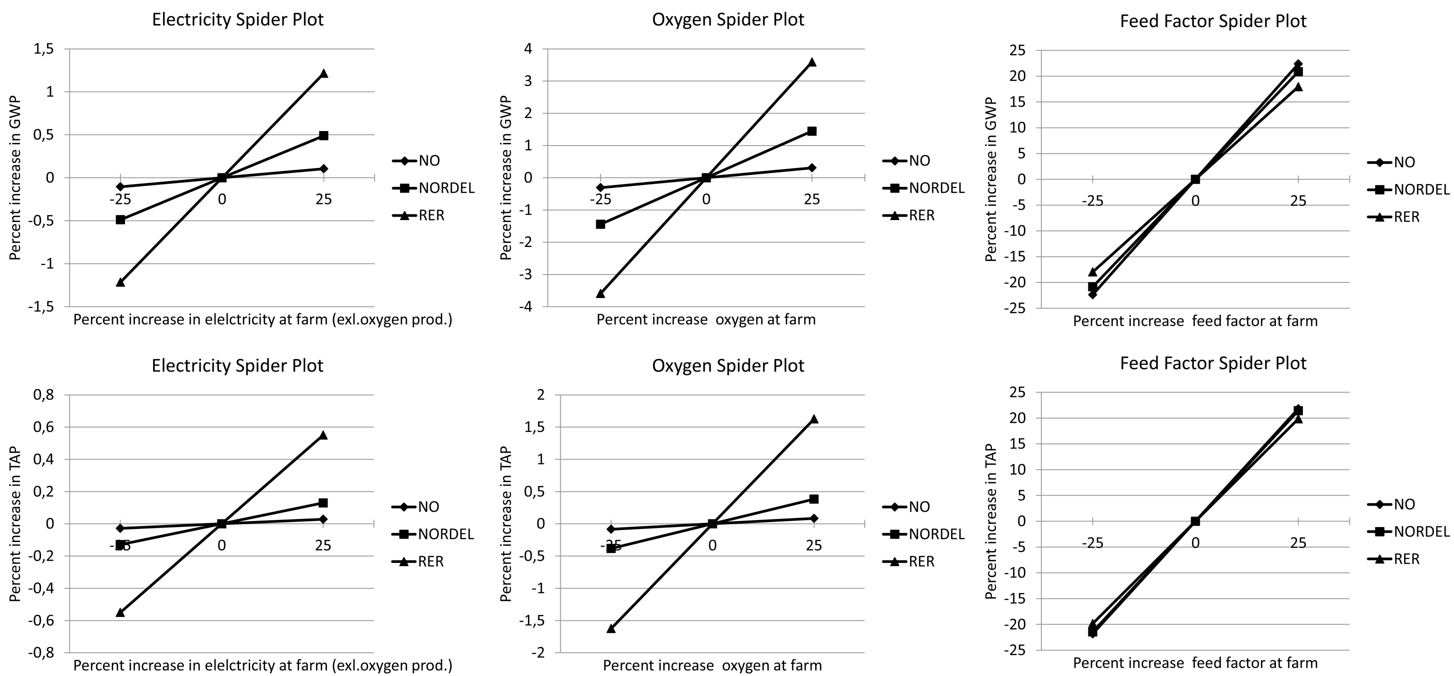


Figure 25: Spider plot for GWP and TAP, left $+-25\%$ electricity, middle $+-25\%$ oxygen, right $+-25\%$ feed factor.

The top three graphs in figure 26 shows the sensitivity for the FEP. We see, as mentioned earlier, that the change in electricity, both base requirements and oxygen production, have little to no impact on the category. Data quality for the electricity an the oxygen production is therefore not critical for this category. We see on the graph on the right that the change in feed factor have very near an 1:1 ratio with increase in impact. This means that data on the feed production and feed factor is critical to get a usable result.

The bottom three figure 26 shows the sensitivity for the MET. The same is true for this category as is stated for the FEP category.

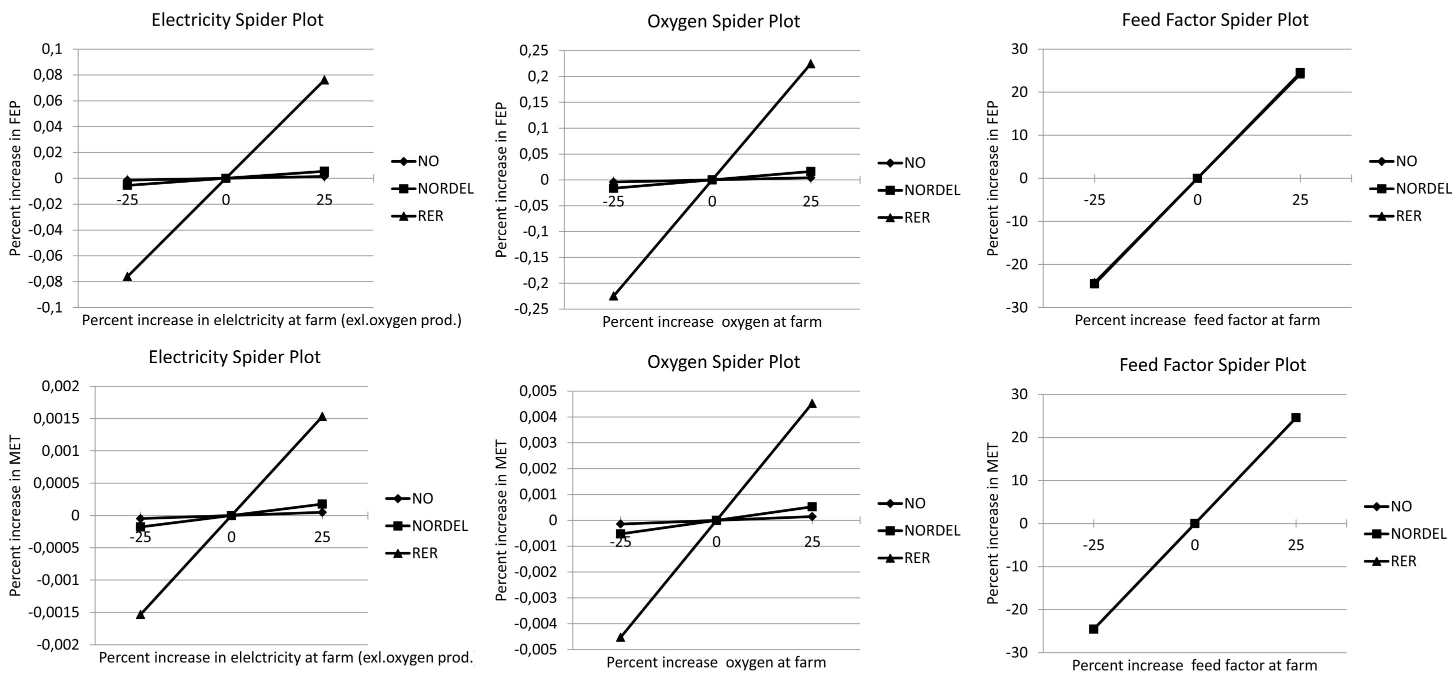


Figure 26: Spider plot for FEP and MET, left + − 25% electricity, middle + − 25% oxygen, right + − 25% feed factor.

# 7 Conclusion

The LCA was set out to compare the closed and the open fish farming systems, and to explore the differences in environmental impacts. The findings is summarized as follows.

The closed fish farming system have a significantly higher electricity requirement than the open system. This leads to a higher sensitivity to changes in environmental impacts from the electricity, and the results suggest that the impacts in the climate change and terrestrial acidification category is sensitive to change in electricity mix. Minimizing the oxygen use at the closed farm would yield some lower impacts directly from the farm. If this effects the feed efficiency in any way then it should not take precedence seeing the much higher sensitivity of the fish feed on impacts.

The fish feed production is the dominating process in all four main categories, with it being close to a hundred percent of the marine ecotoxicity and freshwater eutrophication categories. This means that the data quality for the feed production and the feed factor on the farm is crucial to get a usable result. From an environmental and economical standpoint the focus for the closed system as well as for open systems should be optimizing feed efficiency on the farms. Feed factor is closely related to the environmental impacts, and can for the categories in this LCA nearly be used as an multiplicator for the impacts. If the closed system manages to establish a feed factor lower than the open systems of today, as is suggested by Thorarensen 2011 [10], the impacts from closed fish farms will be significantly lower than it is in open systems today.

An argument for closed systems is the collection of faeces and other sediments from the fish cage, and a small difference in marine eutrophication was found, approx. 10% less impacts from the closed farm. Local effects or the use of the collected sediments is not covered in the LCA. One concept might be to utilize the collected sediments for fertilizing, this would decrease the impacts from the closed fish farm further by decreasing the impacts from the fertilizer industry. This have not been implemented yet and is still in the concept stage, other uses might also be possible.

Assuming a Norwegian el-mix used at the farm, the study finds the closed system to have very similar environmental impacts as the open system for the categories discussed in this LCA.

## 7.1 Future

Continued work on this subject will most likely happen in the near future seeing that there are several closed farm concepts in the work in the industry today. When a full scale closed system have been tested for a full cycle, I think that an exhaustive LCA should be conducted to fully map the environmental impacts. This study should look into the increased use of electric energy compared to farms today, and what implications that would have on environmental impacts. E.g. how much electric energy will the Norwegian fish industry use compared today if all farms were closed fish farms?

The clean energy supplied by Norwegian hydro-power plants may be perfect for the closed fish farming industry to flourish in Norway. How the energy will fare in other countries with a dirtier el-mix is an interesting question, and should be explored further.

This LCA might be a couple of years premature, in the next few years data from larger size implementation of closed systems will become available, which opens for more thorough LCA's to be conducted.

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# A Inventory

Table 5: Inventory of the foreground to foreground, $\boldsymbol{A}_{\mathrm{ff}}$

| Full Name | Unit | OFF. | SP. | ST. | FP.0.95 | FP.1.10 | FP.1.25 | FT.0.95 | FT.1.10 | FT.1.25 | FTsp. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Open Fish Farm | t | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Smolt Production | t | 0,02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Smolt Transport | tkm | 2,3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (0.95) | t | 0,95 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (1.10) | t | 1,1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Prod. (1.25) | t | 1,25 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (0.95) | tkm | 760 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (1.10) | tkm | 880 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. ff (1.25) | tkm | 1000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feed Tran. sp | tkm | 0 | 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6: Inventory of the background to foreground

| Background Name | Foreground Process Name | Amount | Unit |
|---|---|---|---|
| Electricity | Open Fish Farm | 26,00 | kWh |
| Diesel | Open Fish Farm | 25,19 | kg |
| Petrol | Open Fish Farm | 0,29 | kg |
| Electricity | Closed Fish Farm | 736,18 | kWh |
| Diesel | Closed Fish Farm | 22,34 | kg |
| Petrol | Closed Fish Farm | 0,29 | kg |
| Electricity | Smolt Production | 4230,00 | kWh |
| Diesel | Smolt Production | 127,50 | kg |
| Oxygen | Smolt Production | 500,00 | kg |
| Transport Ship | Smolt Transport | 1,00 | tkm |
| Electricity | Feed Production | 111,11 | kWh |
| Propane | Feed Production | 1,22 | kg |
| Diesel | Feed Production | 0,23 | kg |
| Natural gas | Feed Production | 11,58 | Nm3 |
| Soybean Meal | Feed Production | 250,00 | kg |
| Fave Beans | Feed Production | 50,00 | kg |
| Rape Meal | Feed Production | 50,00 | kg |
| Rape Oil | Feed Production | 190,00 | kg |
| Wheat Grains | Feed Production | 125,00 | kg |
| Fish Meal | Feed Production | 150,00 | kg |
| Fish Oil | Feed Production | 115,00 | kg |
| Fish Meal By-products | Feed Production | 20,00 | kg |
| Wheat Gluten | Feed Production | 50,00 | kg |
| Transport Ship | Feed Transport - off | 1,00 | tkm |
| Transport Lorry | Feed Transport - sp | 1,00 | tkm |

Table 7: Inventory of the open system foreground stressor intensities

| Stressor Name | Foreground Process Name | Amount | Unit |
|---|---|---|---|
| NOx to air | Open Fish Farm | 2,25E+00 | kg |
| Carbon monoxide air | Open Fish Farm | 4,88E-01 | kg |
| Sulfur oxides, air | Open Fish Farm | 1,48E-01 | kg |
| Particulates, < 10 um air | Open Fish Farm | 1,58E-01 | kg |
| Carbon dioxide, air | Open Fish Farm | 8,42E+01 | kg |
| Aldehydes, air | Open Fish Farm | 3,60E-02 | kg |
| Toc, total organic carbon, water | Open Fish Farm | 2,01E-01 | kg |
| Benzene, air | Open Fish Farm | 4,74E-04 | kg |
| Toluene, air | Open Fish Farm | 2,08E-04 | kg |
| Xylenes (total), air | Open Fish Farm | 1,45E-04 | kg |
| Propylene, air | Open Fish Farm | 1,31E-03 | kg |
| 1,3-butadiene, air | Open Fish Farm | 1,99E-05 | kg |
| Formaldehyde, air | Open Fish Farm | 5,99E-04 | kg |
| Acetaldehyde, air | Open Fish Farm | 3,90E-04 | kg |
| Acrolein, air | Open Fish Farm | 4,70E-05 | kg |
| Naphthalene, air | Open Fish Farm | 4,31E-05 | kg |
| Acenaphthylene, water | Open Fish Farm | 2,57E-06 | kg |
| Acenaphthene, air | Open Fish Farm | 7,21E-07 | kg |
| Fluorene, air | Open Fish Farm | 1,48E-05 | kg |
| Phenanthrene, air | Open Fish Farm | 1,49E-05 | kg |
| Anthracene, air | Open Fish Farm | 9,50E-07 | kg |
| Fluoranthene, air | Open Fish Farm | 3,87E-06 | kg |
| Pyrene, air | Open Fish Farm | 2,43E-06 | kg |
| Benzo[a]anthracene, air | Open Fish Farm | 8,53E-07 | kg |
| Benzo[a]pyrene | Open Fish Farm | 9,55E-08 | kg |
| Dibenz(a,h)anthracene, air | Open Fish Farm | 2,96E-07 | kg |
| Nitrogen, water, ocean | Open Fish Farm | 4,00E+01 | kg |
| Phosphorus, total, water, ocean | Open Fish Farm | 8,00E+00 | kg |
| Solids, inorganic, water, ocean | Open Fish Farm | 3,50E+02 | kg |
| NOx to air | Smolt Production | 1,13E+01 | kg |
| Carbon monoxide air | Smolt Production | 2,44E+00 | kg |
| Sulfur oxides, air | Smolt Production | 7,46E-01 | kg |
| Particulates, < 10 um air | Smolt Production | 7,97E-01 | kg |
| Carbon dioxide, air | Smolt Production | 4,22E+02 | kg |
| Aldehydes, air | Smolt Production | 1,80E-01 | kg |
| Toc, total organic carbon, water | Smolt Production | 9,26E-01 | kg |
| Benzene, air | Smolt Production | 2,40E-03 | kg |
| Toluene, air | Smolt Production | 1,05E-03 | kg |
| Xylenes (total), air | Smolt Production | 7,33E-04 | kg |
| Propylene, air | Smolt Production | 6,63E-03 | kg |
| 1,3-butadiene, air | Smolt Production | 1,01E-04 | kg |
| Formaldehyde, air | Smolt Production | 3,03E-03 | kg |
| Acetaldehyde, air | Smolt Production | 1,97E-03 | kg |
| Acrolein, air | Smolt Production | 2,38E-04 | kg |
| Naphthalene, air | Smolt Production | 2,18E-04 | kg |
| Acenaphthylene, water | Smolt Production | 1,30E-05 | kg |
| Acenaphthene, air | Smolt Production | 3,65E-06 | kg |
| Fluorene, air | Smolt Production | 7,51E-05 | kg |
| Phenanthrene, air | Smolt Production | 7,56E-05 | kg |
| Anthracene, air | Smolt Production | 4,81E-06 | kg |
| Fluoranthene, air | Smolt Production | 1,96E-05 | kg |
| Pyrene, air | Smolt Production | 1,23E-05 | kg |
| Benzo[a]anthracene, air | Smolt Production | 4,32E-06 | kg |
| Benzo[a]pyrene | Smolt Production | 4,83E-07 | kg |
| Dibenz(a,h)anthracene, air | Smolt Production | 1,50E-06 | kg |
| NOx to air | Feed Production | 5,25E-02 | kg |
| Carbon monoxide air | Feed Production | 2,24E-02 | kg |
| SO2, air | Feed Production | 1,12E-04 | kg |
| Sulfur oxides, air | Feed Production | 1,36E-03 | kg |
| Particulates, < 10 um air | Feed Production | 3,29E-03 | kg |
| Carbon dioxide, air | Feed Production | 2,69E+01 | kg |
| Aldehydes, air | Feed Production | 3,27E-04 | kg |
| Toc, total organic carbon, water | Feed Production | 4,04E-03 | kg |
| Benzene, air | Feed Production | 4,37E-06 | kg |
| Toluene, air | Feed Production | 1,91E-06 | kg |
| Xylenes (total), air | Feed Production | 1,33E-06 | kg |
| Propylene, air | Feed Production | 1,21E-05 | kg |
| 1,3-butadiene, air | Feed Production | 1,83E-07 | kg |
| Formaldehyde, air | Feed Production | 5,52E-06 | kg |
| Acetaldehyde, air | Feed Production | 3,59E-06 | kg |
| Acrolein, air | Feed Production | 4,33E-07 | kg |
| Naphthalene, air | Feed Production | 3,97E-07 | kg |
| Acenaphthylene, water | Feed Production | 2,37E-08 | kg |
| Acenaphthene, air | Feed Production | 6,64E-09 | kg |
| Fluorene, air | Feed Production | 1,37E-07 | kg |
| Phenanthrene, air | Feed Production | 1,38E-07 | kg |
| Anthracene, air | Feed Production | 8,75E-09 | kg |
| Fluoranthene, air | Feed Production | 3,56E-08 | kg |
| Pyrene, air | Feed Production | 2,24E-08 | kg |
| Benzo[a]anthracene, air | Feed Production | 7,86E-09 | kg |
| Benzo[a]pyrene | Feed Production | 8,80E-10 | kg |
| Dibenz(a,h)anthracene, air | Feed Production | 2,73E-09 | kg |
| Lead, air | Feed Production | 9,35E-08 | kg |
| Nitrous oxide, air | Feed Production | 7,99E-04 | kg |
| Methane, biogenic, air | Feed Production | 4,90E-04 | kg |
| Voc, volatile organic compounds | Feed Production | 1,03E-03 | kg |

Table 9: Inventory of the closed system foreground stressor intensities

| Stressor Name | Foreground Process Name | Amount | Unit |
|---|---|---|---|
| NOx to air | Closed Fish Farm | 2,00E+00 | kg |
| Carbon monoxide air | Closed Fish Farm | 4,34E-01 | kg |
| Sulfur oxides, air | Closed Fish Farm | 1,31E-01 | kg |
| Particulates, < 10 um air | Closed Fish Farm | 1,40E-01 | kg |
| Carbon dioxide, air | Closed Fish Farm | 7,48E+01 | kg |
| Aldehydes, air | Closed Fish Farm | 3,19E-02 | kg |
| Toc, total organic carbon, water | Closed Fish Farm | 1,80E-01 | kg |
| Benzene, air | Closed Fish Farm | 4,20E-04 | kg |
| Toluene, air | Closed Fish Farm | 1,84E-04 | kg |
| Xylenes (total), air | Closed Fish Farm | 1,28E-04 | kg |
| Propylene, air | Closed Fish Farm | 1,16E-03 | kg |
| 1,3-butadiene, air | Closed Fish Farm | 1,76E-05 | kg |
| Formaldehyde, air | Closed Fish Farm | 5,32E-04 | kg |
| Acetaldehyde, air | Closed Fish Farm | 3,46E-04 | kg |
| Acrolein, air | Closed Fish Farm | 4,17E-05 | kg |
| Naphthalene, air | Closed Fish Farm | 3,82E-05 | kg |
| Acenaphthylene, water | Closed Fish Farm | 2,28E-06 | kg |
| Acenaphthene, air | Closed Fish Farm | 6,40E-07 | kg |
| Fluorene, air | Closed Fish Farm | 1,32E-05 | kg |
| Phenanthrene, air | Closed Fish Farm | 1,32E-05 | kg |
| Anthracene, air | Closed Fish Farm | 8,42E-07 | kg |
| Fluoranthene, air | Closed Fish Farm | 3,43E-06 | kg |
| Pyrene, air | Closed Fish Farm | 2,15E-06 | kg |
| Benzo[a]anthracene, air | Closed Fish Farm | 7,57E-07 | kg |
| Benzo[a]pyrene | Closed Fish Farm | 8,47E-08 | kg |
| Dibenz(a,h)anthracene, air | Closed Fish Farm | 2,63E-07 | kg |
| Nitrogen, water, ocean | Closed Fish Farm | 3,60E+01 | kg |
| Phosphorus, total, water, ocean | Closed Fish Farm | 5,00E+00 | kg |
| Solids, inorganic, water, ocean | Closed Fish Farm | 2,10E+02 | kg |
| NOx to air | Smolt Production | 1,13E+01 | kg |
| Carbon monoxide air | Smolt Production | 2,44E+00 | kg |
| Sulfur oxides, air | Smolt Production | 7,46E-01 | kg |
| Particulates, < 10 um air | Smolt Production | 7,97E-01 | kg |
| Carbon dioxide, air | Smolt Production | 4,22E+02 | kg |
| Aldehydes, air | Smolt Production | 1,80E-01 | kg |
| Toc, total organic carbon, water | Smolt Production | 9,26E-01 | kg |
| Benzene, air | Smolt Production | 2,40E-03 | kg |
| Toluene, air | Smolt Production | 1,05E-03 | kg |
| Xylenes (total), air | Smolt Production | 7,33E-04 | kg |
| Propylene, air | Smolt Production | 6,63E-03 | kg |
| 1,3-butadiene, air | Smolt Production | 1,01E-04 | kg |
| Formaldehyde, air | Smolt Production | 3,03E-03 | kg |
| Acetaldehyde, air | Smolt Production | 1,97E-03 | kg |
| Acrolein, air | Smolt Production | 2,38E-04 | kg |
| Naphthalene, air | Smolt Production | 2,18E-04 | kg |
| Acenaphthylene, water | Smolt Production | 1,30E-05 | kg |
| Acenaphthene, air | Smolt Production | 3,65E-06 | kg |
| Fluorene, air | Smolt Production | 7,51E-05 | kg |
| Phenanthrene, air | Smolt Production | 7,56E-05 | kg |
| Anthracene, air | Smolt Production | 4,81E-06 | kg |
| Fluoranthene, air | Smolt Production | 1,96E-05 | kg |
| Pyrene, air | Smolt Production | 1,23E-05 | kg |
| Benzo[a]anthracene, air | Smolt Production | 4,32E-06 | kg |
| Benzo[a]pyrene | Smolt Production | 4,83E-07 | kg |
| Dibenz(a,h)anthracene, air | Smolt Production | 1,50E-06 | kg |
| NOx to air | Feed Production | 5,25E-02 | kg |
| Carbon monoxide air | Feed Production | 2,24E-02 | kg |
| SO2, air | Feed Production | 1,12E-04 | kg |
| Sulfur oxides, air | Feed Production | 1,36E-03 | kg |
| Particulates, < 10 um air | Feed Production | 3,29E-03 | kg |
| Carbon dioxide, air | Feed Production | 2,69E+01 | kg |
| Aldehydes, air | Feed Production | 3,27E-04 | kg |
| Toc, total organic carbon, water | Feed Production | 4,04E-03 | kg |
| Benzene, air | Feed Production | 4,37E-06 | kg |
| Toluene, air | Feed Production | 1,91E-06 | kg |
| Xylenes (total), air | Feed Production | 1,33E-06 | kg |
| Propylene, air | Feed Production | 1,21E-05 | kg |
| 1,3-butadiene, air | Feed Production | 1,83E-07 | kg |
| Formaldehyde, air | Feed Production | 5,52E-06 | kg |
| Acetaldehyde, air | Feed Production | 3,59E-06 | kg |
| Acrolein, air | Feed Production | 4,33E-07 | kg |
| Naphthalene, air | Feed Production | 3,97E-07 | kg |
| Acenaphthylene, water | Feed Production | 2,37E-08 | kg |
| Acenaphthene, air | Feed Production | 6,64E-09 | kg |
| Fluorene, air | Feed Production | 1,37E-07 | kg |
| Phenanthrene, air | Feed Production | 1,38E-07 | kg |
| Anthracene, air | Feed Production | 8,75E-09 | kg |
| Fluoranthene, air | Feed Production | 3,56E-08 | kg |
| Pyrene, air | Feed Production | 2,24E-08 | kg |
| Benzo[a]anthracene, air | Feed Production | 7,86E-09 | kg |
| Benzo[a]pyrene | Feed Production | 8,80E-10 | kg |
| Dibenz(a,h)anthracene, air | Feed Production | 2,73E-09 | kg |
| Lead, air | Feed Production | 9,35E-08 | kg |
| Nitrous oxide, air | Feed Production | 7,99E-04 | kg |
| Methane, biogenic, air | Feed Production | 4,90E-04 | kg |
| Voc, volatile organic compounds | Feed Production | 1,03E-03 | kg |

# B Results

Table 11: Results open 0.95 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,25E+03 | 1,28E-01 | 2,94E-01 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,31E+02 | 3,12E+01 | 4,91E+00 | 1,27E-02 | 9,07E+01 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,70E+01 | 8,31E-02 | 8,73E-02 | 1,21E-04 | 1,67E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 9,34E+02 | 6,69E+00 | 4,21E+00 | 5,33E-03 | 9,22E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 8,83E+01 | 3,27E+00 | 8,23E+00 | 4,53E-03 | 7,52E+01 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,48E+01 | 5,72E+01 | 1,07E-02 | 2,12E-05 | 7,51E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,64E+01 | 4,04E-01 | 2,88E-01 | 1,02E-03 | 2,53E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,48E-01 | 4,75E-02 | 6,16E-03 | 2,94E-05 | 8,46E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 6,68E-05 | 1,19E-05 | 1,60E-06 | 4,48E-09 | 5,17E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,35E+00 | 7,22E-01 | 8,27E-02 | 1,91E-04 | 1,48E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,31E+00 | 2,41E+00 | 2,58E-01 | 5,63E-04 | 2,44E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,41E+01 | 9,15E-03 | 3,40E-03 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,39E+01 | 1,66E-01 | 4,70E-02 | 1,24E-03 | 2,32E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 1,46E+03 | 7,30E+01 | 2,12E+02 | 4,61E-02 | 1,16E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,25E+03 | 9,81E+01 | 1,65E+01 | 4,10E-02 | 1,12E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,30E+01 | 1,55E+00 | 1,80E-01 | 5,64E-04 | 1,11E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,16E+01 | 2,67E-03 | 4,94E-03 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 9,90E-02 | 8,80E-02 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,26E+03 | 4,92E-01 | 1,48E+00 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,38E+02 | 3,20E+01 | 7,60E+00 | 1,27E-02 | 9,41E+01 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,71E+01 | 9,61E-02 | 1,30E-01 | 1,21E-04 | 1,68E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 9,43E+02 | 7,78E+00 | 7,75E+00 | 5,33E-03 | 9,26E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,44E+02 | 9,93E+00 | 2,99E+01 | 4,53E-03 | 1,03E+02 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,48E+01 | 5,72E+01 | 1,20E-02 | 2,12E-05 | 7,51E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,67E+01 | 4,30E-01 | 3,72E-01 | 1,02E-03 | 2,55E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,51E-01 | 4,79E-02 | 7,31E-03 | 2,94E-05 | 8,61E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 6,89E-05 | 1,21E-05 | 2,42E-06 | 4,48E-09 | 5,27E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,39E+00 | 7,27E-01 | 9,87E-02 | 1,91E-04 | 1,50E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,37E+00 | 2,42E+00 | 2,81E-01 | 5,63E-04 | 2,47E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,41E+01 | 1,27E-02 | 1,49E-02 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,40E+01 | 1,83E-01 | 1,04E-01 | 1,24E-03 | 2,33E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 2,50E+03 | 1,97E+02 | 6,16E+02 | 4,61E-02 | 1,67E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,28E+03 | 1,02E+02 | 2,77E+01 | 4,10E-02 | 1,13E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,31E+01 | 1,56E+00 | 2,08E-01 | 5,64E-04 | 1,11E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,16E+01 | 3,23E-03 | 6,77E-03 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 1,13E-01 | 1,33E-01 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,25E+03 | 2,69E-01 | 7,53E-01 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,59E+02 | 3,45E+01 | 1,55E+01 | 1,27E-02 | 1,04E+02 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,83E+01 | 2,46E-01 | 6,17E-01 | 1,21E-04 | 1,74E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 9,91E+02 | 1,35E+01 | 2,63E+01 | 5,33E-03 | 9,50E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,58E+02 | 1,16E+01 | 3,53E+01 | 4,53E-03 | 1,10E+02 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,48E+01 | 5,72E+01 | 2,08E-02 | 2,12E-05 | 7,52E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,67E+01 | 4,34E-01 | 3,86E-01 | 1,02E-03 | 2,55E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,59E-01 | 4,88E-02 | 1,02E-02 | 2,94E-05 | 8,98E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,13E-05 | 1,24E-05 | 3,33E-06 | 4,48E-09 | 5,39E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,48E+00 | 7,37E-01 | 1,31E-01 | 1,91E-04 | 1,54E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,51E+00 | 2,44E+00 | 3,38E-01 | 5,63E-04 | 2,54E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,41E+01 | 9,80E-03 | 5,50E-03 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,42E+01 | 2,03E-01 | 1,68E-01 | 1,24E-03 | 2,34E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 1,82E+03 | 1,16E+02 | 3,53E+02 | 4,61E-02 | 1,34E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,35E+03 | 1,10E+02 | 5,51E+01 | 4,10E-02 | 1,17E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,34E+01 | 1,59E+00 | 3,36E-01 | 5,64E-04 | 1,13E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,16E+01 | 1,32E-02 | 3,92E-02 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 2,58E-01 | 6,06E-01 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |

# Table 12: Results open 1.10 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,60E+03 | 1,28E-01 | 2,94E-01 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,46E+02 | 3,12E+01 | 4,91E+00 | 1,27E-02 | 1,05E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,95E+01 | 8,31E-02 | 8,73E-02 | 1,21E-04 | 1,93E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,08E+03 | 6,69E+00 | 4,21E+00 | 5,33E-03 | 1,06E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,00E+02 | 3,27E+00 | 8,23E+00 | 4,53E-03 | 8,69E+01 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,59E+01 | 5,72E+01 | 1,07E-02 | 2,12E-05 | 8,67E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,04E+01 | 4,04E-01 | 2,88E-01 | 1,02E-03 | 2,93E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,63E-01 | 4,75E-02 | 6,16E-03 | 2,94E-05 | 9,77E-02 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,50E-05 | 1,19E-05 | 1,60E-06 | 4,48E-09 | 5,97E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,59E+00 | 7,22E-01 | 8,27E-02 | 1,91E-04 | 1,71E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,71E+00 | 2,41E+00 | 2,58E-01 | 5,63E-04 | 2,81E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 9,15E-03 | 3,40E-03 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,75E+01 | 1,66E-01 | 4,70E-02 | 1,24E-03 | 2,68E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 1,64E+03 | 7,30E+01 | 2,12E+02 | 4,61E-02 | 1,34E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,42E+03 | 9,81E+01 | 1,65E+01 | 4,10E-02 | 1,29E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,47E+01 | 1,55E+00 | 1,80E-01 | 5,64E-04 | 1,28E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,49E+01 | 2,67E-03 | 4,94E-03 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 9,90E-02 | 8,80E-02 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,60E+03 | 4,92E-01 | 1,48E+00 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,54E+02 | 3,20E+01 | 7,60E+00 | 1,27E-02 | 1,09E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,97E+01 | 9,61E-02 | 1,30E-01 | 1,21E-04 | 1,94E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,09E+03 | 7,78E+00 | 7,75E+00 | 5,33E-03 | 1,07E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,60E+02 | 9,93E+00 | 2,99E+01 | 4,53E-03 | 1,19E+02 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,59E+01 | 5,72E+01 | 1,20E-02 | 2,12E-05 | 8,67E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,06E+01 | 4,30E-01 | 3,72E-01 | 1,02E-03 | 2,94E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,66E-01 | 4,79E-02 | 7,31E-03 | 2,94E-05 | 9,94E-02 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,73E-05 | 1,21E-05 | 2,42E-06 | 4,48E-09 | 6,09E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,64E+00 | 7,27E-01 | 9,87E-02 | 1,91E-04 | 1,74E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,78E+00 | 2,42E+00 | 2,81E-01 | 5,63E-04 | 2,85E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 1,27E-02 | 1,49E-02 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,77E+01 | 1,83E-01 | 1,04E-01 | 1,24E-03 | 2,69E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 2,76E+03 | 1,97E+02 | 6,16E+02 | 4,61E-02 | 1,93E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,46E+03 | 1,02E+02 | 2,77E+01 | 4,10E-02 | 1,31E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,48E+01 | 1,56E+00 | 2,08E-01 | 5,64E-04 | 1,28E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,49E+01 | 3,23E-03 | 6,77E-03 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 1,13E-01 | 1,33E-01 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,60E+03 | 2,69E-01 | 7,53E-01 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,76E+02 | 3,45E+01 | 1,55E+01 | 1,27E-02 | 1,20E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,10E+01 | 2,46E-01 | 6,17E-01 | 1,21E-04 | 2,01E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,14E+03 | 1,35E+01 | 2,63E+01 | 5,33E-03 | 1,10E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,75E+02 | 1,16E+01 | 3,53E+01 | 4,53E-03 | 1,27E+02 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,60E+01 | 5,72E+01 | 2,08E-02 | 2,12E-05 | 8,68E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,07E+01 | 4,34E-01 | 3,86E-01 | 1,02E-03 | 2,94E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,74E-01 | 4,88E-02 | 1,02E-02 | 2,94E-05 | 1,04E-01 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,98E-05 | 1,24E-05 | 3,33E-06 | 4,48E-09 | 6,22E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,73E+00 | 7,37E-01 | 1,31E-01 | 1,91E-04 | 1,78E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,93E+00 | 2,44E+00 | 3,38E-01 | 5,63E-04 | 2,93E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 9,80E-03 | 5,50E-03 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,79E+01 | 2,03E-01 | 1,68E-01 | 1,24E-03 | 2,70E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 2,03E+03 | 1,16E+02 | 3,53E+02 | 4,61E-02 | 1,54E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,53E+03 | 1,10E+02 | 5,51E+01 | 4,10E-02 | 1,35E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,52E+01 | 1,59E+00 | 3,36E-01 | 5,64E-04 | 1,30E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,50E+01 | 1,32E-02 | 3,92E-02 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 2,58E-01 | 6,06E-01 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |

# Table 13: Results open 1.25 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,95E+03 | 1,28E-01 | 2,94E-01 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,61E+02 | 3,12E+01 | 4,91E+00 | 1,27E-02 | 1,19E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,21E+01 | 8,31E-02 | 8,73E-02 | 1,21E-04 | 2,19E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,22E+03 | 6,69E+00 | 4,21E+00 | 5,33E-03 | 1,21E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,12E+02 | 3,27E+00 | 8,23E+00 | 4,53E-03 | 9,85E+01 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,71E+01 | 5,72E+01 | 1,07E-02 | 2,12E-05 | 9,83E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,44E+01 | 4,04E-01 | 2,88E-01 | 1,02E-03 | 3,32E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,78E-01 | 4,75E-02 | 6,16E-03 | 2,94E-05 | 1,11E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,32E-05 | 1,19E-05 | 1,60E-06 | 4,48E-09 | 6,76E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,83E+00 | 7,22E-01 | 8,27E-02 | 1,91E-04 | 1,94E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,12E+00 | 2,41E+00 | 2,58E-01 | 5,63E-04 | 3,19E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,46E+01 | 9,15E-03 | 3,40E-03 | 3,46E-06 | 4,46E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,12E+01 | 1,66E-01 | 4,70E-02 | 1,24E-03 | 3,04E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 1,82E+03 | 7,30E+01 | 2,12E+02 | 4,61E-02 | 1,51E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,60E+03 | 9,81E+01 | 1,65E+01 | 4,10E-02 | 1,47E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,65E+01 | 1,55E+00 | 1,80E-01 | 5,64E-04 | 1,45E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,82E+01 | 2,67E-03 | 4,94E-03 | 6,10E-06 | 2,82E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 9,90E-02 | 8,80E-02 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,95E+03 | 4,92E-01 | 1,48E+00 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,69E+02 | 3,20E+01 | 7,60E+00 | 1,27E-02 | 1,23E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,23E+01 | 9,61E-02 | 1,30E-01 | 1,21E-04 | 2,20E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,23E+03 | 7,78E+00 | 7,75E+00 | 5,33E-03 | 1,21E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,77E+02 | 9,93E+00 | 2,99E+01 | 4,53E-03 | 1,35E+02 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,71E+01 | 5,72E+01 | 1,20E-02 | 2,12E-05 | 9,83E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,46E+01 | 4,30E-01 | 3,72E-01 | 1,02E-03 | 3,33E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,81E-01 | 4,79E-02 | 7,31E-03 | 2,94E-05 | 1,13E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,57E-05 | 1,21E-05 | 2,42E-06 | 4,48E-09 | 6,90E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,88E+00 | 7,27E-01 | 9,87E-02 | 1,91E-04 | 1,97E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,19E+00 | 2,42E+00 | 2,81E-01 | 5,63E-04 | 3,23E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,47E+01 | 1,27E-02 | 1,49E-02 | 3,46E-06 | 4,47E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,14E+01 | 1,83E-01 | 1,04E-01 | 1,24E-03 | 3,05E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 3,02E+03 | 1,97E+02 | 6,16E+02 | 4,61E-02 | 2,19E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,63E+03 | 1,02E+02 | 2,77E+01 | 4,10E-02 | 1,48E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,65E+01 | 1,56E+00 | 2,08E-01 | 5,64E-04 | 1,45E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,82E+01 | 3,23E-03 | 6,77E-03 | 6,10E-06 | 2,82E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 1,13E-01 | 1,33E-01 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,95E+03 | 2,69E-01 | 7,53E-01 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,92E+02 | 3,45E+01 | 1,55E+01 | 1,27E-02 | 1,36E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,37E+01 | 2,46E-01 | 6,17E-01 | 1,21E-04 | 2,28E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,29E+03 | 1,35E+01 | 2,63E+01 | 5,33E-03 | 1,24E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,93E+02 | 1,16E+01 | 3,53E+01 | 4,53E-03 | 1,44E+02 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,71E+01 | 5,72E+01 | 2,08E-02 | 2,12E-05 | 9,85E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,47E+01 | 4,34E-01 | 3,86E-01 | 1,02E-03 | 3,34E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,90E-01 | 4,88E-02 | 1,02E-02 | 2,94E-05 | 1,18E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,84E-05 | 1,24E-05 | 3,33E-06 | 4,48E-09 | 7,05E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,97E+00 | 7,37E-01 | 1,31E-01 | 1,91E-04 | 2,02E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,36E+00 | 2,44E+00 | 3,38E-01 | 5,63E-04 | 3,32E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,47E+01 | 9,80E-03 | 5,50E-03 | 3,46E-06 | 4,46E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,15E+01 | 2,03E-01 | 1,68E-01 | 1,24E-03 | 3,06E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 2,24E+03 | 1,16E+02 | 3,53E+02 | 4,61E-02 | 1,75E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,71E+03 | 1,10E+02 | 5,51E+01 | 4,10E-02 | 1,53E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,69E+01 | 1,59E+00 | 3,36E-01 | 5,64E-04 | 1,47E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,83E+01 | 1,32E-02 | 3,92E-02 | 6,10E-06 | 2,83E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 2,58E-01 | 6,06E-01 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |

Table 14: Results closed 0.95 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,25E+03 | 2,10E+00 | 2,94E-01 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,34E+02 | 3,37E+01 | 4,91E+00 | 1,27E-02 | 9,07E+01 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,71E+01 | 2,11E-01 | 8,73E-02 | 1,21E-04 | 1,67E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 9,41E+02 | 1,37E+01 | 4,21E+00 | 5,33E-03 | 9,22E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,29E+02 | 4,36E+01 | 8,23E+00 | 4,53E-03 | 7,52E+01 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 5,90E+01 | 5,15E+01 | 1,07E-02 | 2,12E-05 | 7,51E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,81E+01 | 2,05E+00 | 2,88E-01 | 1,02E-03 | 2,53E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,52E-01 | 5,06E-02 | 6,16E-03 | 2,94E-05 | 8,46E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 6,73E-05 | 1,24E-05 | 1,60E-06 | 4,48E-09 | 5,17E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,31E+00 | 6,80E-01 | 8,27E-02 | 1,91E-04 | 1,48E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,09E+00 | 2,20E+00 | 2,58E-01 | 5,63E-04 | 2,44E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,41E+01 | 2,70E-02 | 3,40E-03 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,40E+01 | 2,98E-01 | 4,70E-02 | 1,24E-03 | 2,32E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 2,97E+03 | 1,58E+03 | 2,12E+02 | 4,61E-02 | 1,16E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,26E+03 | 1,10E+02 | 1,65E+01 | 4,10E-02 | 1,12E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,29E+01 | 1,44E+00 | 1,80E-01 | 5,64E-04 | 1,11E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,16E+01 | 7,84E-03 | 4,94E-03 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 2,31E-01 | 8,80E-02 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,27E+03 | 1,24E+01 | 1,48E+00 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,63E+02 | 5,70E+01 | 7,60E+00 | 1,27E-02 | 9,41E+01 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,75E+01 | 5,79E-01 | 1,30E-01 | 1,21E-04 | 1,68E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 9,80E+02 | 4,44E+01 | 7,75E+00 | 5,33E-03 | 9,26E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 3,67E+02 | 2,32E+02 | 2,99E+01 | 4,53E-03 | 1,03E+02 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 5,91E+01 | 5,15E+01 | 1,20E-02 | 2,12E-05 | 7,51E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,90E+01 | 2,79E+00 | 3,72E-01 | 1,02E-03 | 2,55E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,64E-01 | 6,06E-02 | 7,31E-03 | 2,94E-05 | 8,61E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,63E-05 | 1,95E-05 | 2,42E-06 | 4,48E-09 | 5,27E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,49E+00 | 8,19E-01 | 9,87E-02 | 1,91E-04 | 1,50E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,34E+00 | 2,39E+00 | 2,81E-01 | 5,63E-04 | 2,47E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,42E+01 | 1,27E-01 | 1,49E-02 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,46E+01 | 7,96E-01 | 1,04E-01 | 1,24E-03 | 2,33E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 7,40E+03 | 5,10E+03 | 6,16E+02 | 4,61E-02 | 1,67E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,38E+03 | 2,07E+02 | 2,77E+01 | 4,10E-02 | 1,13E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,32E+01 | 1,68E+00 | 2,08E-01 | 5,64E-04 | 1,11E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,16E+01 | 2,38E-02 | 6,77E-03 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 6,22E-01 | 1,33E-01 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,26E+03 | 6,09E+00 | 7,53E-01 | 1,40E-04 | 2,25E+03 | 4,63E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 2,50E+02 | 1,26E+02 | 1,55E+01 | 1,27E-02 | 1,04E+02 | 4,18E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,29E+01 | 4,82E+00 | 6,17E-01 | 1,21E-04 | 1,74E+01 | 4,01E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,18E+03 | 2,06E+02 | 2,63E+01 | 5,33E-03 | 9,50E+02 | 1,76E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 4,26E+02 | 2,79E+02 | 3,53E+01 | 4,53E-03 | 1,10E+02 | 1,50E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 5,91E+01 | 5,16E+01 | 2,08E-02 | 2,12E-05 | 7,52E+00 | 7,01E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 2,92E+01 | 2,91E+00 | 3,86E-01 | 1,02E-03 | 2,55E+01 | 3,38E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,96E-01 | 8,58E-02 | 1,02E-02 | 2,94E-05 | 8,98E-02 | 9,72E-03 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,63E-05 | 2,75E-05 | 3,33E-06 | 4,48E-09 | 5,39E-05 | 1,48E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,84E+00 | 1,10E+00 | 1,31E-01 | 1,91E-04 | 1,54E+00 | 6,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,96E+00 | 2,89E+00 | 3,38E-01 | 5,63E-04 | 2,54E+00 | 1,86E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,41E+01 | 4,53E-02 | 5,50E-03 | 3,46E-06 | 3,41E+01 | 1,14E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,53E+01 | 1,35E+00 | 1,68E-01 | 1,24E-03 | 2,34E+01 | 4,11E-01 | 1,16E-02 |
| Water depletion | m3 | 4,51E+03 | 2,81E+03 | 3,53E+02 | 4,61E-02 | 1,34E+03 | 1,52E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,68E+03 | 4,45E+02 | 5,51E+01 | 4,10E-02 | 1,17E+03 | 1,36E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,46E+01 | 2,79E+00 | 3,36E-01 | 5,64E-04 | 1,13E+01 | 1,86E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,19E+01 | 3,06E-01 | 3,92E-02 | 6,10E-06 | 2,16E+01 | 2,02E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,66E+04 | 4,74E+00 | 6,06E-01 | 1,80E-04 | 1,66E+04 | 5,96E-02 | 3,81E-03 |

Table 15: Results closed 1.10 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,60E+03 | 2,10E+00 | 2,94E-01 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,49E+02 | 3,37E+01 | 4,91E+00 | 1,27E-02 | 1,05E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 1,97E+01 | 2,11E-01 | 8,73E-02 | 1,21E-04 | 1,93E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,08E+03 | 1,37E+01 | 4,21E+00 | 5,33E-03 | 1,06E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,41E+02 | 4,36E+01 | 8,23E+00 | 4,53E-03 | 8,69E+01 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,02E+01 | 5,15E+01 | 1,07E-02 | 2,12E-05 | 8,67E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,21E+01 | 2,05E+00 | 2,88E-01 | 1,02E-03 | 2,93E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,66E-01 | 5,06E-02 | 6,16E-03 | 2,94E-05 | 9,77E-02 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 7,55E-05 | 1,24E-05 | 1,60E-06 | 4,48E-09 | 5,97E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,55E+00 | 6,80E-01 | 8,27E-02 | 1,91E-04 | 1,71E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,50E+00 | 2,20E+00 | 2,58E-01 | 5,63E-04 | 2,81E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 2,70E-02 | 3,40E-03 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,77E+01 | 2,98E-01 | 4,70E-02 | 1,24E-03 | 2,68E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 3,15E+03 | 1,58E+03 | 2,12E+02 | 4,61E-02 | 1,34E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,44E+03 | 1,10E+02 | 1,65E+01 | 4,10E-02 | 1,29E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,46E+01 | 1,44E+00 | 1,80E-01 | 5,64E-04 | 1,28E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,49E+01 | 7,84E-03 | 4,94E-03 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 2,31E-01 | 8,80E-02 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,62E+03 | 1,24E+01 | 1,48E+00 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,79E+02 | 5,70E+01 | 7,60E+00 | 1,27E-02 | 1,09E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,01E+01 | 5,79E-01 | 1,30E-01 | 1,21E-04 | 1,94E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,12E+03 | 4,44E+01 | 7,75E+00 | 5,33E-03 | 1,07E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 3,83E+02 | 2,32E+02 | 2,99E+01 | 4,53E-03 | 1,19E+02 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,02E+01 | 5,15E+01 | 1,20E-02 | 2,12E-05 | 8,67E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,30E+01 | 2,79E+00 | 3,72E-01 | 1,02E-03 | 2,94E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,79E-01 | 6,06E-02 | 7,31E-03 | 2,94E-05 | 9,94E-02 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,46E-05 | 1,95E-05 | 2,42E-06 | 4,48E-09 | 6,09E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,73E+00 | 8,19E-01 | 9,87E-02 | 1,91E-04 | 1,74E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,75E+00 | 2,39E+00 | 2,81E-01 | 5,63E-04 | 2,85E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,95E+01 | 1,27E-01 | 1,49E-02 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,83E+01 | 7,96E-01 | 1,04E-01 | 1,24E-03 | 2,69E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 7,66E+03 | 5,10E+03 | 6,16E+02 | 4,61E-02 | 1,93E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,56E+03 | 2,07E+02 | 2,77E+01 | 4,10E-02 | 1,31E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,49E+01 | 1,68E+00 | 2,08E-01 | 5,64E-04 | 1,28E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,49E+01 | 2,38E-02 | 6,77E-03 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 6,22E-01 | 1,33E-01 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,61E+03 | 6,09E+00 | 7,53E-01 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 2,67E+02 | 1,26E+02 | 1,55E+01 | 1,27E-02 | 1,20E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,56E+01 | 4,82E+00 | 6,17E-01 | 1,21E-04 | 2,01E+01 | 4,65E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,33E+03 | 2,06E+02 | 2,63E+01 | 5,33E-03 | 1,10E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 4,43E+02 | 2,79E+02 | 3,53E+01 | 4,53E-03 | 1,27E+02 | 1,73E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,03E+01 | 5,16E+01 | 2,08E-02 | 2,12E-05 | 8,68E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,32E+01 | 2,91E+00 | 3,86E-01 | 1,02E-03 | 2,94E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 2,11E-01 | 8,58E-02 | 1,02E-02 | 2,94E-05 | 1,04E-01 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 9,49E-05 | 2,75E-05 | 3,33E-06 | 4,48E-09 | 6,22E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 3,09E+00 | 1,10E+00 | 1,31E-01 | 1,91E-04 | 1,78E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,38E+00 | 2,89E+00 | 3,38E-01 | 5,63E-04 | 2,93E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 4,53E-02 | 5,50E-03 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,90E+01 | 1,35E+00 | 1,68E-01 | 1,24E-03 | 2,70E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 4,72E+03 | 2,81E+03 | 3,53E+02 | 4,61E-02 | 1,54E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,87E+03 | 4,45E+02 | 5,51E+01 | 4,10E-02 | 1,35E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,64E+01 | 2,79E+00 | 3,36E-01 | 5,64E-04 | 1,30E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,53E+01 | 3,06E-01 | 3,92E-02 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 4,74E+00 | 6,06E-01 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |

Table 16: Results closed 1.25 NO, NORDEL, RER

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,95E+03 | 2,10E+00 | 2,94E-01 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,63E+02 | 3,37E+01 | 4,91E+00 | 1,27E-02 | 1,19E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,23E+01 | 2,11E-01 | 8,73E-02 | 1,21E-04 | 2,19E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,23E+03 | 1,37E+01 | 4,21E+00 | 5,33E-03 | 1,21E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 1,52E+02 | 4,36E+01 | 8,23E+00 | 4,53E-03 | 9,85E+01 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,14E+01 | 5,15E+01 | 1,07E-02 | 2,12E-05 | 9,83E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,60E+01 | 2,05E+00 | 2,88E-01 | 1,02E-03 | 3,32E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,81E-01 | 5,06E-02 | 6,16E-03 | 2,94E-05 | 1,11E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,37E-05 | 1,24E-05 | 1,60E-06 | 4,48E-09 | 6,76E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,79E+00 | 6,80E-01 | 8,27E-02 | 1,91E-04 | 1,94E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,90E+00 | 2,20E+00 | 2,58E-01 | 5,63E-04 | 3,19E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,47E+01 | 2,70E-02 | 3,40E-03 | 3,46E-06 | 4,46E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,13E+01 | 2,98E-01 | 4,70E-02 | 1,24E-03 | 3,04E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 3,33E+03 | 1,58E+03 | 2,12E+02 | 4,61E-02 | 1,51E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,61E+03 | 1,10E+02 | 1,65E+01 | 4,10E-02 | 1,47E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,64E+01 | 1,44E+00 | 1,80E-01 | 5,64E-04 | 1,45E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,82E+01 | 7,84E-03 | 4,94E-03 | 6,10E-06 | 2,82E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 2,31E-01 | 8,80E-02 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,96E+03 | 1,24E+01 | 1,48E+00 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 1,94E+02 | 5,70E+01 | 7,60E+00 | 1,27E-02 | 1,23E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,27E+01 | 5,79E-01 | 1,30E-01 | 1,21E-04 | 2,20E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,27E+03 | 4,44E+01 | 7,75E+00 | 5,33E-03 | 1,21E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 3,99E+02 | 2,32E+02 | 2,99E+01 | 4,53E-03 | 1,35E+02 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,14E+01 | 5,15E+01 | 1,20E-02 | 2,12E-05 | 9,83E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,70E+01 | 2,79E+00 | 3,72E-01 | 1,02E-03 | 3,33E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,94E-01 | 6,06E-02 | 7,31E-03 | 2,94E-05 | 1,13E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 9,30E-05 | 1,95E-05 | 2,42E-06 | 4,48E-09 | 6,90E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,97E+00 | 8,19E-01 | 9,87E-02 | 1,91E-04 | 1,97E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,16E+00 | 2,39E+00 | 2,81E-01 | 5,63E-04 | 3,23E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,48E+01 | 1,27E-01 | 1,49E-02 | 3,46E-06 | 4,47E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,20E+01 | 7,96E-01 | 1,04E-01 | 1,24E-03 | 3,05E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 7,93E+03 | 5,10E+03 | 6,16E+02 | 4,61E-02 | 2,19E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,74E+03 | 2,07E+02 | 2,77E+01 | 4,10E-02 | 1,48E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,67E+01 | 1,68E+00 | 2,08E-01 | 5,64E-04 | 1,45E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,83E+01 | 2,38E-02 | 6,77E-03 | 6,10E-06 | 2,82E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 6,22E-01 | 1,33E-01 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |
| Agricultural land occupation | m2a | 2,96E+03 | 6,09E+00 | 7,53E-01 | 1,40E-04 | 2,95E+03 | 6,10E-02 | 4,38E-03 |
| Fossil depletion | kg oil eq | 2,84E+02 | 1,26E+02 | 1,55E+01 | 1,27E-02 | 1,36E+02 | 5,50E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,83E+01 | 4,82E+00 | 6,17E-01 | 1,21E-04 | 2,28E+01 | 5,28E-02 | 3,34E-03 |
| Human toxicity | kg 1,4-DB eq | 1,48E+03 | 2,06E+02 | 2,63E+01 | 5,33E-03 | 1,24E+03 | 2,32E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 4,60E+02 | 2,79E+02 | 3,53E+01 | 4,53E-03 | 1,44E+02 | 1,97E+00 | 9,72E-02 |
| Marine eutrophication | kg N eq | 6,15E+01 | 5,16E+01 | 2,08E-02 | 2,12E-05 | 9,85E+00 | 9,23E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,71E+01 | 2,91E+00 | 3,86E-01 | 1,02E-03 | 3,34E+01 | 4,44E-01 | 5,60E-02 |
| Natural land transformation | m2 | 2,27E-01 | 8,58E-02 | 1,02E-02 | 2,94E-05 | 1,18E-01 | 1,28E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 1,03E-04 | 2,75E-05 | 3,33E-06 | 4,48E-09 | 7,05E-05 | 1,95E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 3,34E+00 | 1,10E+00 | 1,31E-01 | 1,91E-04 | 2,02E+00 | 8,30E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 6,81E+00 | 2,89E+00 | 3,38E-01 | 5,63E-04 | 3,32E+00 | 2,45E-01 | 1,04E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 4,47E+01 | 4,53E-02 | 5,50E-03 | 3,46E-06 | 4,46E+01 | 1,51E-03 | 1,63E-04 |
| Urban land occupation | m2a | 3,27E+01 | 1,35E+00 | 1,68E-01 | 1,24E-03 | 3,06E+01 | 5,40E-01 | 1,16E-02 |
| Water depletion | m3 | 4,93E+03 | 2,81E+03 | 3,53E+02 | 4,61E-02 | 1,75E+03 | 2,00E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 2,05E+03 | 4,45E+02 | 5,51E+01 | 4,10E-02 | 1,53E+03 | 1,78E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,81E+01 | 2,79E+00 | 3,36E-01 | 5,64E-04 | 1,47E+01 | 2,45E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,86E+01 | 3,06E-01 | 3,92E-02 | 6,10E-06 | 2,83E+01 | 2,65E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 2,18E+04 | 4,74E+00 | 6,06E-01 | 1,80E-04 | 2,18E+04 | 7,85E-02 | 3,81E-03 |

Table 17: Results closed 1.10 NO, NORDEL, RER, Oxygen bought

| Name | Unit | d | OFF | SP | ST | FP | FTF | FTS |
|---|---|---|---|---|---|---|---|---|
| Agricultural land occupation | m2a | 2,60E+03 | 3,47E+00 | 2,94E-01 | 1,40E-04 | 2,60E+03 | 5,37E-02 | 4,38E-03 |
| Climate change | kg CO2 eq | 1,08E+03 | 3,17E+02 | 1,65E+01 | 4,10E-02 | 7,33E+02 | 1,57E+01 | 1,06E+00 |
| Fossil depletion | kg oil eq | 2,05E+02 | 9,02E+01 | 4,91E+00 | 1,27E-02 | 1,05E+02 | 4,84E+00 | 3,81E-01 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 2,30E+01 | 3,58E+00 | 8,73E-02 | 1,21E-04 | 1,93E+01 | 4,65E-02 | 3,34E-03 |
| Freshwater eutrophication | kg P eq | 4,62E-01 | 2,26E-01 | 4,94E-03 | 6,10E-06 | 2,29E-01 | 2,34E-03 | 1,02E-04 |
| Human toxicity | kg 1,4-DB eq | 1,22E+03 | 1,54E+02 | 4,21E+00 | 5,33E-03 | 1,06E+03 | 2,04E+00 | 1,36E-01 |
| Ionising radiation | kg U235 eq | 2,87E+02 | 1,90E+02 | 8,23E+00 | 4,53E-03 | 8,69E+01 | 1,73E+00 | 9,72E-02 |
| Marine ecotoxicity | kg 1,4-DB eq | 7,04E+00 | 3,52E+00 | 8,80E-02 | 1,80E-04 | 3,36E+00 | 6,90E-02 | 3,81E-03 |
| Marine eutrophication | kg N eq | 6,03E+01 | 5,16E+01 | 1,07E-02 | 2,12E-05 | 8,67E+00 | 8,12E-03 | 3,68E-04 |
| Metal depletion | kg Fe eq | 3,36E+01 | 3,63E+00 | 2,88E-01 | 1,02E-03 | 2,93E+01 | 3,91E-01 | 5,60E-02 |
| Natural land transformation | m2 | 1,84E-01 | 6,82E-02 | 6,16E-03 | 2,94E-05 | 9,77E-02 | 1,13E-02 | 3,87E-04 |
| Ozone depletion | kg CFC-11 eq | 8,51E-05 | 2,20E-05 | 1,60E-06 | 4,48E-09 | 5,97E-05 | 1,71E-06 | 1,72E-07 |
| Particulate matter formation | kg PM10 eq | 2,82E+00 | 9,45E-01 | 8,27E-02 | 1,91E-04 | 1,71E+00 | 7,31E-02 | 2,71E-03 |
| Photochemical oxidant formation | kg NMVOC | 5,92E+00 | 2,62E+00 | 2,58E-01 | 5,63E-04 | 2,81E+00 | 2,15E-01 | 1,04E-02 |
| Terrestrial acidification | kg SO2 eq | 1,14E+01 | 2,32E+00 | 1,80E-01 | 5,64E-04 | 8,72E+00 | 2,16E-01 | 6,10E-03 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 3,94E+01 | 2,93E-02 | 3,40E-03 | 3,46E-06 | 3,94E+01 | 1,32E-03 | 1,63E-04 |
| Urban land occupation | m2a | 2,83E+01 | 9,00E-01 | 4,70E-02 | 1,24E-03 | 2,68E+01 | 4,75E-01 | 1,16E-02 |
| Water depletion | m3 | 3,63E+03 | 2,07E+03 | 2,12E+02 | 4,61E-02 | 1,34E+03 | 1,76E+01 | 1,30E+00 |
| Climate change | kg CO2 eq | 1,64E+03 | 3,17E+02 | 1,65E+01 | 4,10E-02 | 1,29E+03 | 1,57E+01 | 1,06E+00 |
| Terrestrial acidification | kg SO2 eq | 1,55E+01 | 2,32E+00 | 1,80E-01 | 5,64E-04 | 1,28E+01 | 2,16E-01 | 6,10E-03 |
| Freshwater eutrophication | kg P eq | 2,51E+01 | 2,26E-01 | 4,94E-03 | 6,10E-06 | 2,49E+01 | 2,34E-03 | 1,02E-04 |
| Marine ecotoxicity | kg 1,4-DB eq | 1,92E+04 | 3,52E+00 | 8,80E-02 | 1,80E-04 | 1,92E+04 | 6,90E-02 | 3,81E-03 |

# C Contribution Analysis, Full Results

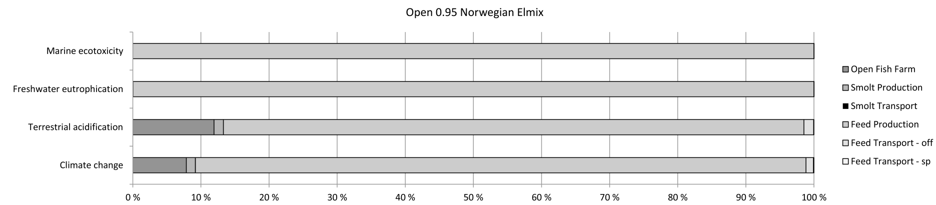


Figure 27: Relative impacts for the open system using NO el-mix and FF 0.95.

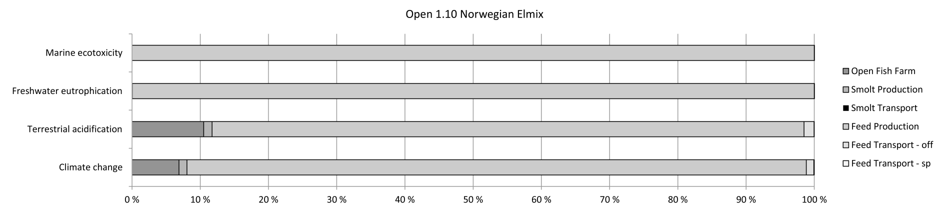


Figure 28: Relative impacts for the open system using NO el-mix and FF 1.10.

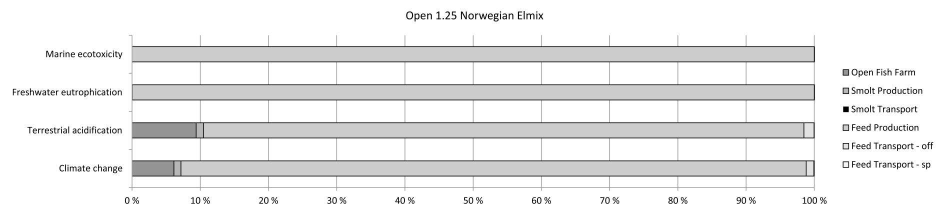


Figure 29: Relative impacts for the open system using NO el-mix and FF 1.25.

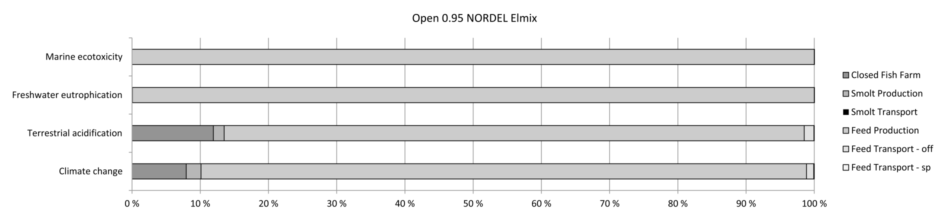


Figure 30: Relative impacts for the open system using NORDEL el-mix and FF 0.95.

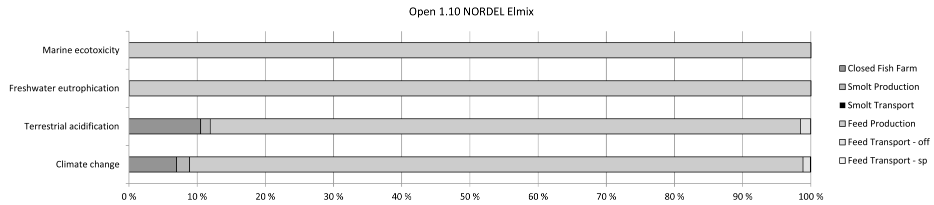


Figure 31: Relative impacts for the open system using NORDEL el-mix and FF 1.10.

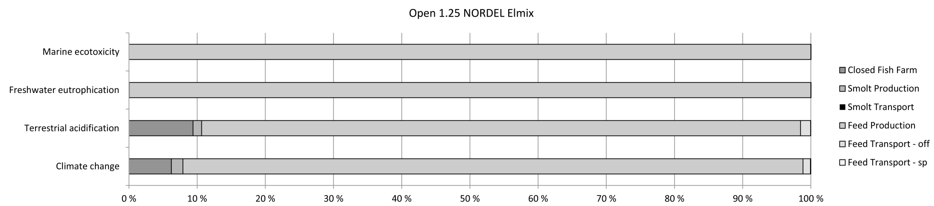


Figure 32: Relative impacts for the open system using NORDEL el-mix and FF 1.25.

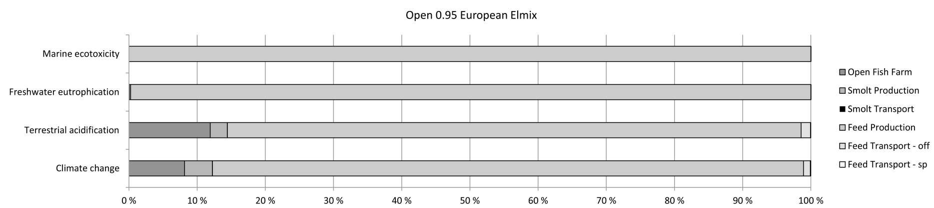


Figure 33: Relative impacts for the open system using RER el-mix and FF 0.95.

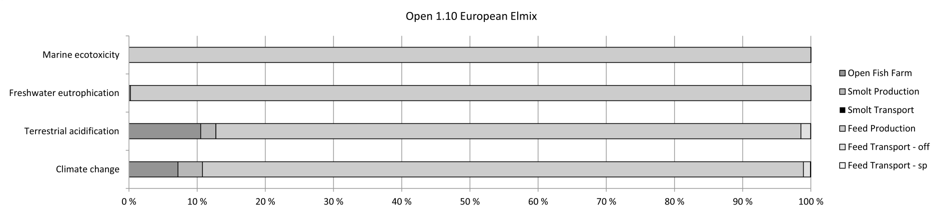


Figure 34: Relative impacts for the open system using RER el-mix and FF 1.10.

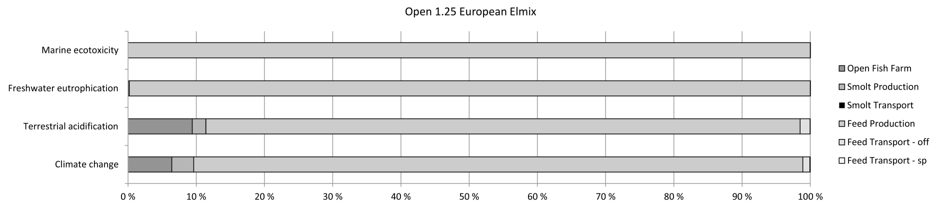


Figure 35: Relative impacts for the open system using RER el-mix and FF 1.25.

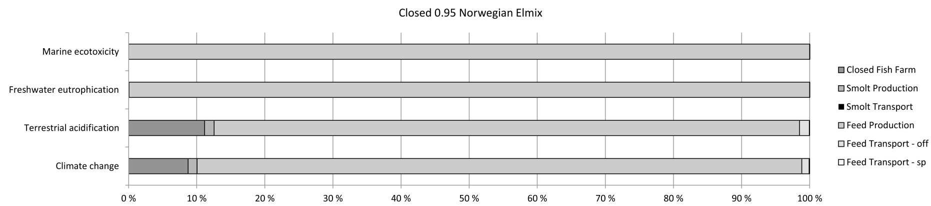


Figure 36: Relative impacts for the closed system using NO el-mix and FF 0.95.

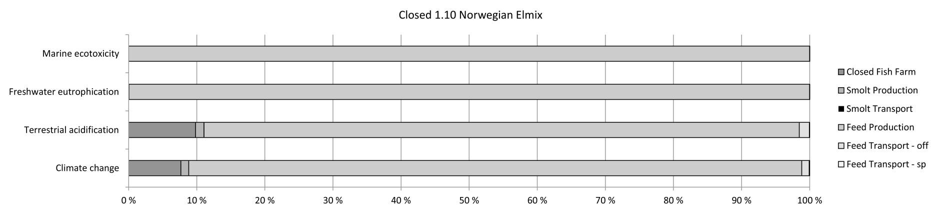


Figure 37: Relative impacts for the closed system using NO el-mix and FF 1.10.

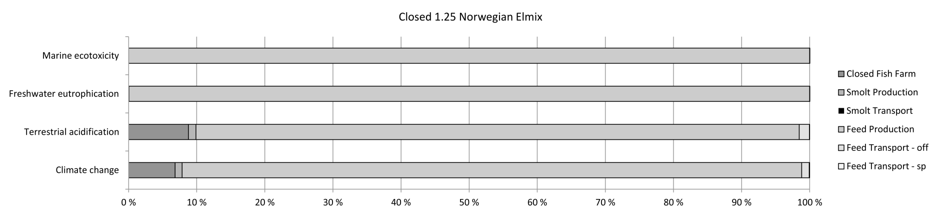


Figure 38: Relative impacts for the closed system using NO el-mix and FF 1.25.

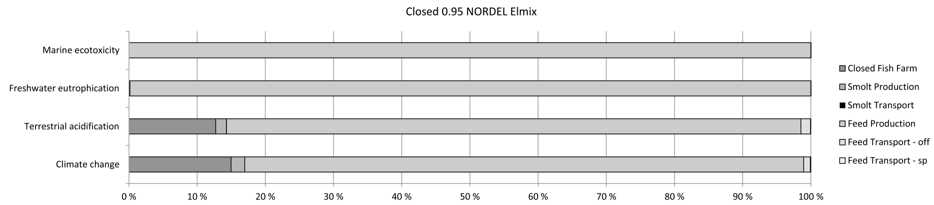


Figure 39: Relative impacts for the closed system using NORDEL el-mix and FF 0.95.

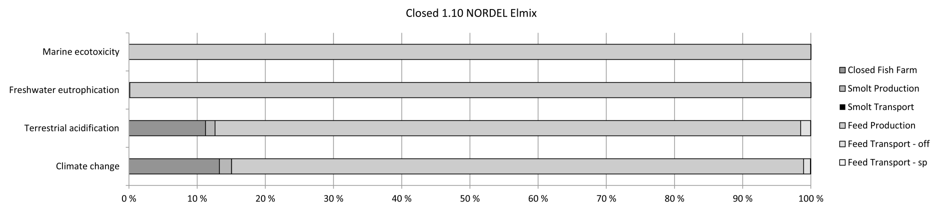


Figure 40: Relative impacts for the closed system using NORDEL el-mix and FF 1.10.

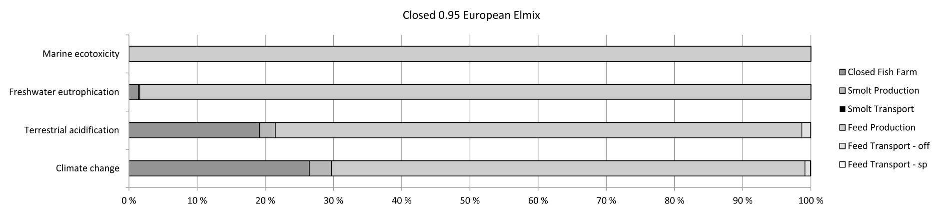


Figure 41: Relative impacts for the closed system using RER el-mix and FF 0.95.

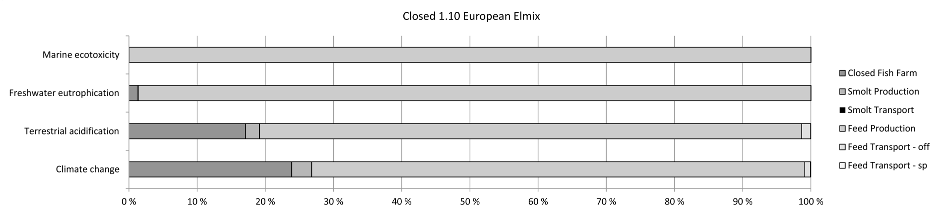


Figure 42: Relative impacts for the closed system using RER el-mix and FF 1.10.

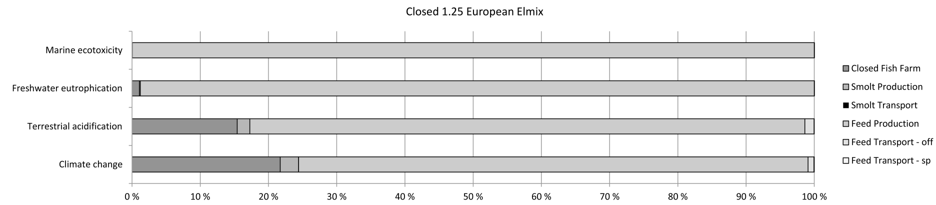


Figure 43: Relative impacts for the closed system using RER el-mix and FF 1.25.

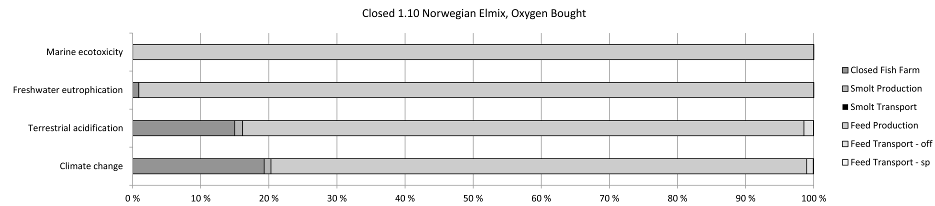


Figure 44: Relative impacts for the closed system using NO el-mix and FF 1.10, oxygen is bought.

# D Specialization Project 2013

The following is the specialization project that was written during the autumn of 2013. This paper covers the basic LCA theory and contains a literature review of LCA methodology used in earlier aquaculture LCA's.

NTNU
Norwegian University of
Science and Technology

IVT-Faculty,
Institute of Marine Technology

# TMR4570 - Fisheries and Marine Resources, Specialization Project

Stud. tech. Ole Jonny Nyhus

## Life Cycle Assessment of Farmed Salmon, Comparing a Closed with an Open Sea Cage System

(Livssyklusanalyse av lakseoppdrett med sammenligning av et lukket med et åpent anlegg i sjø)

The amount of fish farmed in Norway has tripled over the last 15 years, and Norwegian aquaculture has become a 30 billion kroner industry. This massive production increase makes it increasingly important to understand the environmental impacts the industry creates.

As an example, Norwegian fish farms are struggling with resistant salmon lice, and farms might be forced to slaughter the salmon earlier than wanted. This might create a strong incentive for developing and testing out new solutions that might solve the problem. The company Aquafuture in Brønnøysund is developing a closed fish cage solution for use in the Norwegian fish farming industry. This closed system, which collects the water from a depth too deep for the salmon lice, might be a possible solution to the lice problem. The system is now being tested on a fish farm located at Møllebogen in Bindal commune, in the middle of Norway. If this system is technologically and economically viable, we might see a push towards closed fish cage use in aquaculture. It is therefore an interesting question to ask, how environmentally friendly such a solution might be compared to the open cage systems of today?

This specialization project covers the preliminary work leading up to a master thesis where the candidate shall use LCA to compare closed systems with open fish cage systems used in salmon farming today. Another goal is to find key points of impact contribution for the closed cage system, such that environmental improvements can be made.

In this specialization project the candidate shall perform the following main parts:

- Describe the theory and practice of the LCA method including (a) Goal and scope, (b) Life cycle inventory, (c) Life cycle impact assessment and (d) Interpretation
- a literature review of the LCA practice used in fish farming today and
- draft the goal and scope part of the LCA covering (a) Goal of LCA, (b) System flowchart, (c) System boundaries and (d) Choice of Functional Unit.

The evaluation will put focus on whether the work is well documented or not. The work shall be edited as far as possible as a research report with a summary, conclusions, list of references, list of contents etc. The candidate shall emphasize on making the text clear and readable. A thorough description and discussion of the results, including presentations in tables and/or graphics, will be important as basis for evaluation of the work.

Material developed as part of the work, including software or physical equipment, is part of the delivery. Documentation of correct use of such shall further as far possible be included. Any expenses for travelling, copying and telephoning must be carried by the student as long as other agreements are not settled. If unforeseen difficulties are met by the candidate during the work that will require changes in the task description, the department must be contacted without delay. The work shall be delivered in 1 electronic and 2 hardback duplicates.

MTS, November 2013
Harald Ellingsen
professor

# Preface

This paper was written the autumn for 2013 and concludes my specialization project leading up to my Master's thesis. The paper has subject code TMR4570, and amounts to 7.5 ECTS points.

It has been a challenge to delve deep into a subject I never even had heard of, but it have really sparked my interest for both environmental science and aquaculture. It was my step-mother that put me in contact with a company in Brønnøysund that was developing this new closed fish cage, and I am really glad she did, it has inspired me to work hard this semester to get to grasp the science of LCA for use in aquaculture.

Last but not least I want to thank Professor Harald Ellingsen for guidance and for pushing me in the direction of environmental science and LCA.

Ole Jonny Nyhus
Trondheim, June 2, 2014

**Abstract**

The purpose of this paper is to lay the foundation for the comparative LCA of a closed salmon fish farm vs. an open fish farm. The closed system is being developed by Aquafuture in Brønnøysund, and is a closed system for fish farming in the marine environment. The key driver for developing this system is the major problem of salmon lice the industry is having.

LCA consists of four phases; the goal and scope phase, where the goal and methodology of the study is chosen; the life cycle inventory, where the data is collected and structured; the life cycle impact assessment, where the impacts from the production system is calculated; and lastly the interpretation, where the LCA conclusions are made.

A review of the state of the art regarding methods used in LCA on aquaculture have been done. The most common functional unit was 1 tonne live fish at farm gate. Allocation method used were mainly different partitioning methods. A broad spectrum of impact categories were analyzed, most commonly GWP, AP, EP and toxicity.

Lastly the goal and scope phase of the LCA was started. Functional unit of 1 tonne of live fish were chosen, with system boundary at farm gate. Smolt, feed and infrastructure production was included. The internally developed LCA software ARDA together with the background database Ecoinvent will be used in the study.

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# 1 Introduction

In the last fifteen years, Norwegian salmon farming industry have grown at an astounding rate, producing 300 thousand tonnes in 1997 to over 1200 today [1]. With this growth ecological issues like parasites and illnesses have become a part of the daily enterprise for farmers. One of the most critical problems Norwegian fish farms is facing, is an increase of salmon lice in the farmed and the natural salmon population [2]. The salmon louse (Lepeophtheirus salmonis) is a parasite found naturally in Norwegian waters, living of the skin and the blood of the salmonid species, e.g. salmon and rainbow trout [3] [4]. While the correlation between the increase of salmon farming and the increase of salmon lice in the natural population is well founded [5–7], not every study agree that there is a causation between lice in salmon farms and decline in natural salmon population [8]. The fact that lice from the fish farms will cause increase of lice in the natural population is not disputed, the question is rather if the increase in lice among the natural population will cause a decline in size. Whether or not this is the case, it's important for the industry to use the precautionary principle, and instigate countermeasures against the parasite.

The salmon lice is also financially harming the industry, costing Norwegian fish farms over 500 million NOK annually in direct loses and for countermeasures like chemical disinfection [3]. The summer of 2013 the lice infection of wild Sea Trout became so severe that several farms had to slaughter the salmon earlier than planned, some regions even needed a total stop in production to manage the problem [9]. The fish farm companies concedes that the way the industry is run today is not sustainable, and technological solutions are needed.

A possible solution to the lice problem is to isolate the farmed salmon from the surrounding waters using a closed fish farming system. This would greatly decrease the chances of infecting the farm population with the louse, seeing that a farm without lice would have to be infected from the external, i.e. the water which the lice travels through. A new design of such a farming system is being developed by the company Aquadesign in Brønnøysund.

The concept design, see figure 1, is based on holding the salmon in a bag in stead of a net pen. The water is pumped from 25m depth and is injected into the bag at the top, creating a whirlpool effect that keeps it circulating. The water is released into the surrounding waters through a hole at the bottom of the bag. Two tubes carries the waste from the bottom of the bag onto land, one tube for dead fish, and one for the sediment that settles to the sides and drops down due to the circulation in the bag. The dead fish get collected by a grid and that way gets separated from the other sediment, it's then pumped up by use of compressed air. The sediments, i.e. the waste from the fish etc., gets collected in a separate compartment, and gets pumped to the surface.

The system got extra oxygenating of the water, either in the form of liquid oxygen stored in tanks on land, or by machines that collects oxygen from the air and injects it into the water. Keeping the water oxygenated is key to maximize the growth of the salmon though the year [10].

To decrease the likelihood of salmon escaping the farm uses a fish net like the ones they use in open cage farming. This net encompasses the fish pen, that way should the fish get out of the bag they would not escape into the wild.

A study by the Veterinary Institute of Norway, studying the effects on the fish farmed in the closed system, was started in 2011. The study began with a seven month period where the fish was followed closely. Next the fish was split in two cages, one closed, and one open net pen. The study then had three types of set up; closed to closed; closed to open; and open to open (the fish from the nearby open net pen continued in the same pen). The fish was slaughtered the autumn of 2013. Regarding lice, the study concludes that there is possible to keep infection in the closed system close to zero all through the production cycle. Keeping the lice infection below the level where disinfection is required is important, and is a key driver for this new technology. Other issues like cold sores and damage on the fishes fins and gills needed to be addressed [11]

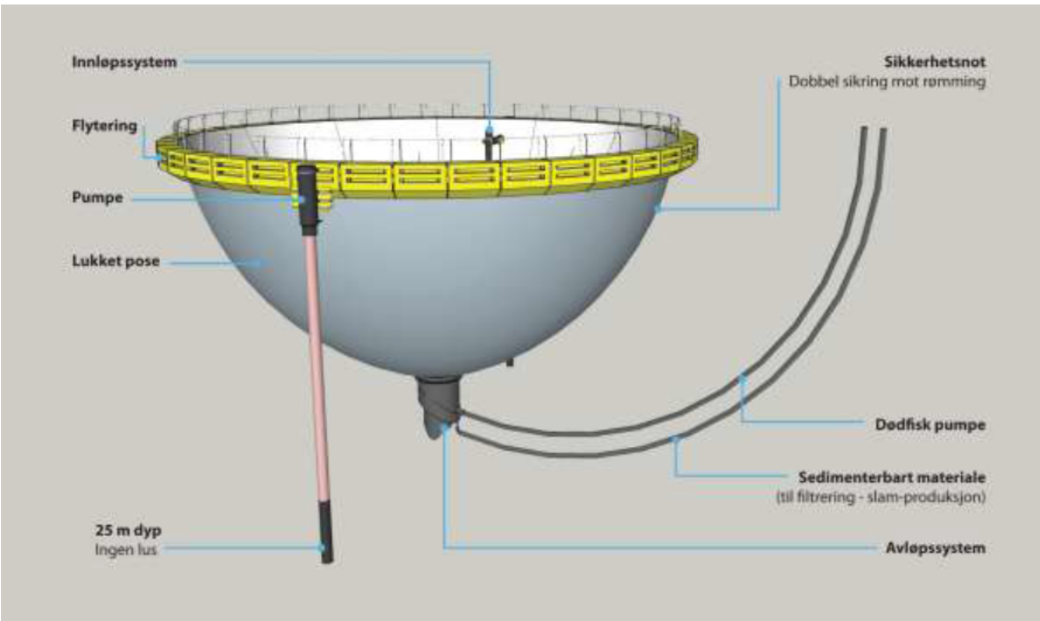


Figure 1: system design of closed fish farm

Technological issues aside, if this technology is viable to supplement or substitute the open net pens used in the industry today, it is important to compare the environmental impacts it may have compared to a open system. Studying the closed system rises questions regarding electricity use and feed conversion ratio, seeing that those two parameters might be what puts the two systems apart. Studies have shown that construction of the fish farm can be neglected [12], this was concluded due to it having small environmental impacts compared to rest of the fish farming cycle. Disregarding construction we might see that there is mostly the pumping and oxygenation of the water that is the obvious difference between the systems. If the cost of the pumping and oxygen production is large, then this could be a significant factor. A review done by Thorarensen et al. 2011 [10] found that salmon farmed in closed systems have a feed conversion ratio (FCR) [1] of between 0.9 and 1.0, suggesting that FCR is slightly lower for closed systems than for open systems, which have a mean of 1.02. Seeing that the feed production has been found to be the key component in studies on environmental impacts [13], this might favour the closed systems. This conclusion must be taken with a pinch of salt and it should be taken into account that the FCR varies greatly across geography and practice.

The basis for this paper and the following master thesis is comparing the environmental impacts of the closed system developed in Brønnøysund with a open net pen. For this I will use Life Cycle Assessment methodology (LCA). In this paper I will first describe the LCA methodology step by step; then I will do a literature review of LCA studies on fish farming, highlighting the methods they used; and lastly I will draft the first part of the LCA, i.e. the goal and scope of the study.

## 1.1 Life Cycle Assessment

LCA is based on knowing the environmental impacts from the product we want to study. These do not only stem from the product production itself, but from the whole system of processes delivering resources to make the product, e.g. a simplified system like the one shown in figure 2. The emissions associated with the production of the salmon comes not only from the farming itself, but from a whole range of processes leading up to the fish farm, e.g. the electricity and feed production etc.. In this system the variable y is the external demand for the product. This unit is called "the functional unit", the unit might be a fillet of salmon, or a kg of salmon depending on the system in question.

The arrows in the figure are resource requirements between two processes, it is them we need to find to calculate the environmental impacts the system creates. An example of resource requirement for a fish farm is feed.

The zigzagged arrows symbolizes the emissions from each process, An example of emission are carbon dioxide ($CO_2$). Emissions are divided into two categories, direct and indirect. The first are the emissions from each process viewed on their own, while the

[1] Feed conversion ratio is the weight of feed divided on the weight of the fish produced

latter are the emissions created by the other processes as a result of the requirements from the process in question. For example a direct emission from producing a fillet of salmon might be the excrements from the fish released into the surrounding waters, while an example of an indirect emission might be $CO_2$, stemming from the power plant burning gas to create electricity for the fish farm. The total emissions from a system are the sum of the direct and the indirect emissions (1):

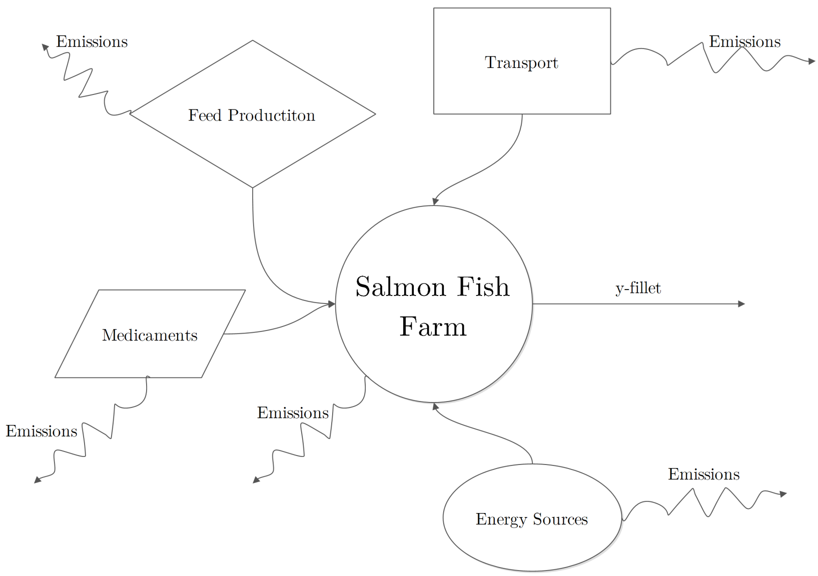


Figure 2: simplified salmon farming system

$$\text{Total emissions} = \text{Direct emissions} + \text{Indirect emissions} \tag{1}$$

By knowing these emissions we are able to calculate the environmental impacts stemming from the production of the functional unit, i.e. the fish in the case of the simplified system [14].

### 1.1.1 Four Phases

There are four phases in an LCA; the goal and scope phase, where we define how the study will be carried out; the life cycle inventory (LCI), where all the data is collected and structured; the life cycle impact assessment (LCIA), where the impacts from the system is quantified; and last the life cycle interpretation, where the results are discussed and interpreted. In the next few sections I will go through the theory of each of these, starting with the goal and scope phase.

# 2 Goal and Scope

## 2.1 Goal

The first question to ask when starting an LCA is why the study is done, what's the goal of the study. This question needs to be answered in the Goal and Scope phase of the LCA study. Different goals may change how we need to model the system, and what analysis methods we need to use. The goal and scope of the study is often a combined decision between the one who makes the product, the commissioner; and the one who carries out the study, the practitioner. Reasons for carrying out a study may be to explore of the products life cycle, or for comparing products to find which is the most environmentally friendly; in other cases LCA studies may be intended to be used in marketing of the product [15, p. 74].

The scope of the study is chosen based on the goal of the study, therefore the goal must first be clearly defined. Curran's LCA Handbook [16, p. 44] defines four main types of LCAs; the first is a single system with intended internal use of results, the goal is to analyse the product to identify opportunities to make it more environmentally friendly, and to establish a baseline for future product improvements; the second type is a single system with intended external use of results, the goal here is to make a environmental product declaration, or for use in marketing; the third type are a comparative analysis with intended internal use of results, the goal here is to compare different design options for a company's product, or to compare with existing products already on the market; the last type is a comparative analysis with intended external use of results, the goal here is to defend a product from criticism and public concerns regarding the products environmental performance compared to alternative products. Another goal may be to use the LCA in marketing comparing the product to the competition.

In any case the ISO states that the goal of the study "shall unambiguously state the intended application, the reason for the study and the intended audience" [17].

## 2.2 Scope

The scoping of the study includes the choice of level of detail, what systems and processes to include, the functional unit, the allocation method to use (see section 4.6), system boundary, impact categories and interpretation methods (see section 6) [16, p. 45].

### 2.2.1 Functional Unit

The functional unit is the reference flow, the quantification of the function of the product from which all other flows of the modelled flows are related [15, p. 76]. The ISO [17] states that the functional unit shall be consistent with the goal and the scope of the study, and that the purpose of the functional unit is to provide a reference which the input and output data are normalized. The functional unit shall be clearly defined and measurable. For single product LCA the choice of functional unit is rather arbitrary, as long as it quantifies the function of the product, e.g. 1 kg or 1 tonne of salmon are both viable choices [15, p. 76]. For comparative studies the choice of functional unit is more critical, and must take into account the differences between the compared products like strength, durability or in the use phase of the product [16, p. 46]. For example two cars that are to be compared both have the same impacts due to production but one car have a lifespan of 200 thousand km while the other only have 150 thousand km, if the cars have the same production phase the impacts per kilometre will be larger for the car with the lower lifespan distance.

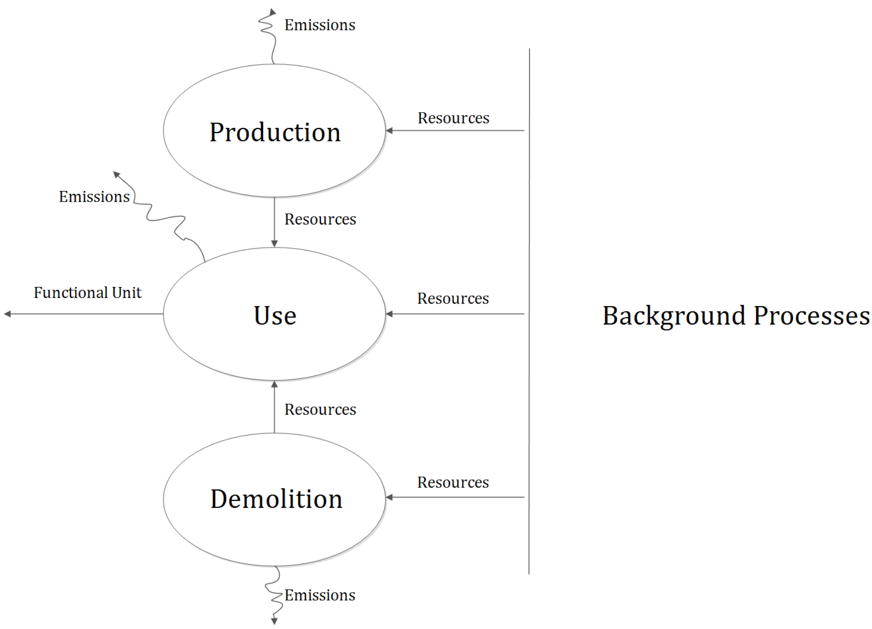


Figure 3: simple system with production, use and demolition phase, with use of background processes from background database such as Ecoinvent

### 2.2.2 System Boundary

The system boundary determines which processes are included in the foreground system, and has to be consistent with the goal and the scope of the study [17]. Here the choice of what life cycle phases to include must be chosen [16, p. 47], these are most commonly production, use and demolition phases [14]. Any choice of exclusion of phases or processes from the study can only be done only if it doesn't change the conclusion of the study [17]. The use of cut of criteria such as mass, energy, and environmental significance shall be clearly described and discussed in the study [17].

A good way to structure the system boundary is in a flow chart, showing the different phases and processes as nodes with arrows signifying the slows of the system. An example of this can be seen in figure 3. Here the different flows and inter-relationships of the system is visualized, emissions can also be included in the flowchart, see the zigzagged lines. We distinguish between foreground and background processes; the foreground processes are the ones the practitioner collects data from, i.e. the ones that is being modeled, and is within the system boundary; while the background processes are processes like resource extraction and refinement, energy production, energy mixes etc., that have been modeled and compiled by companies that specializes on background databases [14], e.g. Ecoinvent database [18]. In figure 3 the foreground processes are on the left while the background processes are on the right. There will of course be many sub processes that also need to be modeled, but the principle is the same.

Take for example a salmon fish farm, where we want to find the impacts from farming salmon. The system boundary might be the farm gate, i.e. when the fish is delivered to slaughter; or it might be at market, i.e. when the fish are delivered to grosser. The cut-of might be that all processes that contributes less than one percent to the mass input is excluded.

### 2.2.3 Impact Categories

This paper will focus on the ReCiPe 2008 life cycle impact assessment method [19]. It's a method based on Ecoindicator 99 and CML, using both mid- and endpoint category indicators. The method contains all the different impact categories:

- Climate Change (CC, GWP)
- Acidification (AP)
- Eutrophication (EP)
- Ozone Depletion (ODP)

- Toxicity (HT, ET)
- Human Health Damage Due to PM10 and Ozone
- Ionising Radiation
- Impacts of Land Use (LD)
- Water Depletion (WD)
- Mineral Resource Depletion (MRD)
- Fossil Fuel Depletion (FFD)

See section 5 on how climate change, acidification, eutrophication and toxicity are calculated. The chosen impact categories shall be justified and consistent with the goal and scope of the study, and they shall reflect the environmental issues associated with the product [17].

When deciding whether to use midpoint or endpoint characterization factors, the pros and cons of the two must be discussed. The endpoint characterization factors are more relevant, and are more relatable to a reader than the midpoint factors; but they are also less certain, and vice versa [20]. In LCAs done on farmed fish midpoint indicators are usually used (see section 7.1.4).

When the goal and the scope of the study has been defined the collection and structuring of data can start, called the LCI phase.

# 3 Life cycle Inventory

While the goal and scope phase gave the initial plan for carrying out the LCA, the LCI phase is the first phase of the plans execution. In this phase the needed data are collected from the systems processes, then they are validated and compiled in such a way that they are related to the functional unit [17].

As the goal of the LCA is to find the impacts stemming from a external demand, e.g. 1 kg of farmed salmon, we need to find way to model the production system so as to find the different flows of resources from the nodes of the system. A node may be a single process or a phase in the production system. One way to model the system was developed by Wassily Leontief in the nineteen forties [21] [20], he developed the Input-Output Analysis which deal with the interconnectivity of the different processes of producing products and services. Leontief got the Nobel price in economics for the development of the model, now known as the Leontief model [14]. In this section the calculation stages of the Leontief model will be shown and explained.

## 3.1 The System Interconnectivity

The thought is to model the different input and outputs of the process nodes, and to find the production from each node associated with the external demand. In figure 4, a simple two node production system is modelled. The arrows between the production nodes 1 and 2 symbolizes the amount of resources required from the other process, we call this requirement $a$. The arrows labelled $y$ symbolizes the external demand, i.e. the functional unit. Equation (2) contains the definition of $a$, and (3) for the definition of $y$:

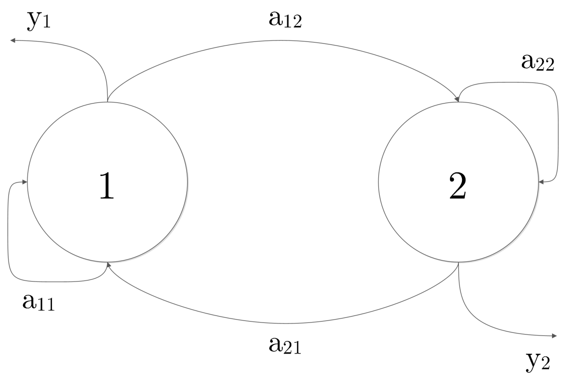


Figure 4: simple production system

$$a_{\mathrm{ij}} = \frac{\text{demand required from node }_{\mathrm{i}}}{\text{(per) unit output of node }_{\mathrm{j}}} \tag{2}$$

$$y_{\mathrm{i}} = \text{external demand put on node }_{\mathrm{i}} \tag{3}$$

Equation (2) can be structured with the different demands in a matrix with rows i and columns j. See equation (4) for definition of the requirements matrix $\boldsymbol{A}$:

$$\boldsymbol{A} = \begin{Bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{Bmatrix} \tag{4}$$

The rows of $\boldsymbol{A}$ can be read as: "from node i"; and the columns as: "to node j". The $\boldsymbol{A}$ matrix does not include the external demand.

The external demand $y$ can be structured as a vector, we call it $\boldsymbol{y}$. Equation (5) defines the vector, the rows can be read as: "external demand put on node i":

$$\boldsymbol{y} = \begin{Bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{Bmatrix} \tag{5}$$

It might be time to ask the question of what variables that are known. When doing a LCI all the requirements of the $\boldsymbol{A}$ matrix is found through research, and the external demand vector is defined at the start of the LCA when the functional unit and the goal of the LCA is defined. The one unknown is now the production output from a given process, we call it $x_i$, defined in equation (6):

$$x_i = \text{units produced in node i for a required demand} \tag{6}$$

Equation (7) shows the production output in vector form:

$$\boldsymbol{x} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \tag{7}$$

The $\boldsymbol{x}$ vector contains the total output of production from the nodes due to the external demand put on the nodes.

The interconnectivity of the system can now be structured. To calculate the output from the different nodes the system of equations can be set up, see (8) for the system shown in figure 4, and see (9) for the general system of equations:

$$\begin{aligned} x_1 &= a_{11}x_1 + a_{12}x_2 + y_1 \\ x_2 &= a_{21}x_1 + a_{22}x_2 + y_2 \end{aligned} \tag{8}$$

$$\begin{aligned} x_1 &= a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n + y_1 \\ x_2 &= a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n + y_2 \\ &\vdots \\ x_n &= a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n + y_n \end{aligned} \tag{9}$$

Looking at equation (8), we see the production of node 1 is determined by the following; the external demand of node 1, plus the demand from the node itself per unit output times the units output from itself, and lastly plus the demand from node 2 per unit times the unites output of node 2. The second equation is vice versa. The system as been generalized in equation (9) [14].

## 3.2 The Leontief Approaches

The system (9) can now be expressed in matrix form seen in equation (10):

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{10}$$

The unknown vector is $\mathbf{x}$, so we follow the following procedure,(10) to (11) to (12) to (13), to find $\mathbf{x}$.

$$\mathbf{x} - \mathbf{A}\mathbf{x} = \mathbf{y} \tag{11}$$

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y} \tag{12}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{13}$$

The matrix $\mathbf{I}$ is called the identity matrix and contains one on the diagonal and zeroes everywhere else. The inverse ($\mathbf{I}$-$\mathbf{A}$) matrix is called the Leontief matrix $\mathbf{L}$ (14).

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{14}$$

$$\mathbf{x} = \mathbf{L}\mathbf{y} \tag{15}$$

To explain the contents of the $\mathbf{L}$ matrix, the relationships within the equation (15) can help us understand. As $\mathbf{x}$ is the production output for each node, and $\mathbf{y}$ is the external demand from each node, the Leontief $\mathbf{L}$ must be the production output from each node per unit external demand from the nodes. The matrix (16) shows how the Leontief for the system illustrated in figure 4, and (17) shows the Leontief for a general system [14].

$$\mathbf{L} = \begin{Bmatrix} 1 - a_{11} & -a_{12} \\ -a_{21} & 1 - a_{22} \end{Bmatrix}^{-1} \tag{16}$$

$$\mathbf{L} = \begin{Bmatrix} 1 - a_{11} & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & 1 - a_{22} & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & 1 - a_{nn} \end{Bmatrix}^{-1} \tag{17}$$

The leontief matrix is always square but it must be ensured that the $(\mathbf{I} - \mathbf{A})$ matrix can be inverted to the Leontief matrix. Mathematically a $n \times n$ matrix, $\mathbf{L}$, is invertible if and only if the *rank* $\mathbf{L} = n$, thus if and only if *det* $\mathbf{L} \neq 0$ [22, pp. 297-299] [23, pp. 315-318].

For the Leontief model however the processes have to be self sustaining. This means that the matrix to be inverted has to fulfill the Hawkins-Simon condition. To satisfy the condition the *leading principal minors*, $|\mathbf{L}_i|$ [24, pp. 309], all has to be positive, equation (18) shows the third *leading principal minor* of the matrix $\mathbf{L}$, and see equation (19) for definition of the H.S. condition [25] [26].

$$|\mathbf{L}_3| = \begin{vmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{vmatrix} \tag{18}$$

$$|\mathbf{L}_i| > 0 \tag{19}$$

Now that the production output matrix $\mathbf{x}$ has been found, the next step on the way to finding the environmental impacts from a system can be taken [14].

## 3.3 Transport Modelling

Transportation are the process of moving a product from one location or process, to another. Transportation might contribute a large part to the environmental impacts and needs some special attention regarding how it's modeled. There are three main ways to model transportation, Transporter Input, Receiver Aggregated, and last Receiver Input [14].

In Transporter Input a transportation process node is put between the processes where transport is happening. This way the process of transportation, we can name it T, get the transported product from the delivering process, and delivers transportation of unit tonne kilometer to the second process. The problem with this method is that no product is delivered to the second process, only transportation. The practitioner who uses this method must be careful when interpreting the results from these processes.

Receiver Aggregated aggregates the transportation into the receiving process, integrating the transport requirement into the requirements of the receiving process. The problem with this method is that the impacts stemming from transportation can't be distinguished from the impacts of the process itself.

The last way of modeling, the Receiver Input method, makes transportation its own process in the foreground, see figure 5 how this is modeled. Using this method we see the impacts from transportation in the $D_{pro,f}$ matrix, this is because it's a foreground process.

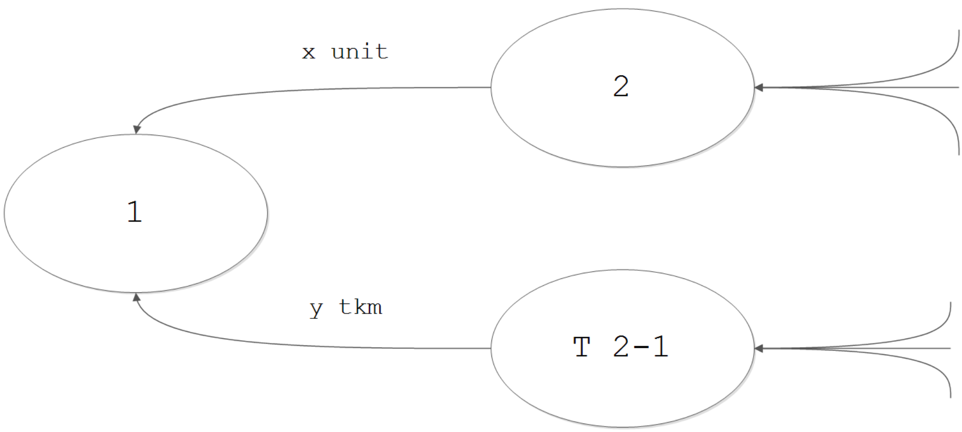


Figure 5: receiver input method for delivery of x units from process 1 to process 2, resulting in y tkm of transport

# 4 Life Cycle Impact Assessment

On the way to finding the environmental impacts from a given process node, the emissions from each process needs to be found. After the Leontief matrix was found in the last section the production outputs from each process associated with the external demand was found. Next a matrix of stressors per production output needs to be structured in such a way that the total emissions from the system can be calculated. Next a matrix containing the impacts per units of the stressors needs to be compiled. This will make it possible to calculate the different impacts divided on both the stressors, and the processes. A matrix containing the contributions to the impact categories associated with the stressors is needed to reach the goal of describing the impacts from each stressor and process [14].

## 4.1 Stressor Matrix

The stressor intensity matrix $\mathbf{S}$ contains the different stressors associated with the output of each processes, i.e. per unit. It must be collected like the requirements in the LCI. It is structured by stressors in the rows, and processes in the columns. A stressor is a more general term used of emissions when dealing with contribution analysis. Equation (20) shows the stressor intensity matrix $\mathbf{S}$ with $m$ stressors and $n$ processes:

$$\mathbf{S} = \begin{Bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ s_{m1} & s_{m3} & \cdots & s_{mn} \end{Bmatrix} \tag{20}$$

The stressor vector $\mathbf{e}$ (21)(22) contains the total stressors of the system associated with the given demand $\mathbf{y}$:

$$\mathbf{e} = \mathbf{S}\mathbf{x} \tag{21}$$

Where the vector $\mathbf{e}$ is given for $m$ stressors:

$$\mathbf{e} = \begin{Bmatrix} e_1 \\ e_2 \\ \vdots \\ e_m \end{Bmatrix} \tag{22}$$

To distinguish between the processes we use $\hat{\mathbf{x}}$ [2] instead of $\mathbf{x}$, and we get instead $\mathbf{E}$ (23).

[2] $\hat{\mathbf{x}}$ is the matrix with the vector $\mathbf{x}$ on the diagonal and zeroes elsewhere.

$$\mathbf{E} = \mathbf{S}\hat{\mathbf{x}} \tag{23}$$

The stressor matrix $\mathbf{E}$ (24) contains the stressors $m$, associated with the $n$ processes.

$$\mathbf{E} = \begin{Bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{m1} & e_{m3} & \cdots & e_{mn} \end{Bmatrix} \tag{24}$$

[14]

## 4.2 The Contribution Matrix

The contribution matrix contains the contribution of each stressor to the impact categories. It is structured with impact categories in arbitrary order in the rows, and stressors in the order of the stressors from the stressor matrix in the columns, see equation (25), $m$ stressors , and $k$ impact categories:

$$\mathbf{C} = \begin{Bmatrix} c_{11} & c_{12} & \cdots & c_{1m} \\ c_{21} & c_{22} & \cdots & c_{2m} \\ \cdots & \cdots & \ddots & \vdots \\ c_{k1} & c_{k3} & \cdots & c_{km} \end{Bmatrix} \tag{25}$$

[14]

## 4.3 Impact Vector & Matrix

There are three basic ways to structure the impacts, the impact vector $\mathbf{d}$ that contains the total impact from all $k$ categories, the impact process matrix $\mathbf{D}_{\text{pro}}$ that contains the impacts associated with the $n$ processes, and the impact stressor matrix $\mathbf{D}_{\text{str}}$ that contains the impacts associated with the $m$ stressors.

To obtain the stressor matrix the contribution matrix must be multiplied by the stressor vector (26), this will give a vector with the total impacts in all $k$ impact categories (27):

$$\mathbf{d} = \mathbf{C}\boldsymbol{e} \tag{26}$$

$$\mathbf{d} = \begin{Bmatrix} d_1 \\ d_2 \\ \vdots \\ d_k \end{Bmatrix} \tag{27}$$

To obtain the process impact matrix $\mathbf{D}_{pro}$, the contribution matrix must be multiplied by the stressor matrix, see (28), this will give a matrix with $k$ impact categories associated and distributed on the $n$ processes, see (29). This matrix contains the direct impacts from each process:

$$\mathbf{D}_{pro} = \mathbf{CE} \tag{28}$$

$$\mathbf{D}_{pro} = \begin{Bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{k1} & d_{k3} & \cdots & d_{kn} \end{Bmatrix} \tag{29}$$

To obtain the stressor impact matrix $\mathbf{D}_{str}$, the contribution matrix must be multiplied by the stressor vector hat[3] (30), this gives a matrix with $k$ impact categories associated with the $m$ stressors (31):

$$\mathbf{D}_{str} = \mathbf{C}\hat{\mathbf{e}} \tag{30}$$

$$\mathbf{D}_{str} = \begin{Bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{k1} & d_{k3} & \cdots & d_{km} \end{Bmatrix} \tag{31}$$

[14]

## 4.4 Foreground and Background Modeling

As stated in section 2 it is necessary to model the production system in a foreground and a background part. The foreground to foreground requirements is structured in matrix $\mathbf{A}_{ff}$,

[3] $\hat{\mathbf{e}}$ is the matrix with the vector $\boldsymbol{e}$ on the diagonal and zeros elsewhere.

i.e. the internal flow between the foreground processes. Similarly foreground to background $\mathbf{A}_{\mathrm{fb}}$ (often zero), background to foreground $\mathbf{A}_{\mathrm{bf}}$, and background to background $\mathbf{A}_{\mathrm{bb}}$. The requirement matrix $\mathbf{A}$ can then be structured as in (32):

$$\mathbf{A} = \begin{Bmatrix} \mathbf{A}_{\mathrm{ff}} & \mathbf{A}_{\mathrm{fb}} \\ \mathbf{A}_{\mathrm{bf}} & \mathbf{A}_{\mathrm{bb}} \end{Bmatrix} \tag{32}$$

Similarly the stressor intensity matrix and the external demand must be structured with a foreground and a background matrix and vector, $\mathbf{S}_{\mathrm{f}}$ and $\mathbf{S}_{\mathrm{b}}$ in (33), and $\mathbf{y}_{\mathrm{f}}$ and $\mathbf{y}_{\mathrm{b}}$ in (34):

$$\mathbf{S} = \begin{Bmatrix} \mathbf{S}_{\mathrm{f}} & \mathbf{S}_{\mathrm{b}} \end{Bmatrix} \tag{33}$$

$$\mathbf{y} = \begin{Bmatrix} \mathbf{y}_{\mathrm{f}} \\ \mathbf{y}_{\mathrm{b}} \end{Bmatrix} \tag{34}$$

[14]

## 4.5 Total Foreground Impacts

As stated in 4.3, $\mathbf{D}_{\mathrm{pro}}$ contains the direct impacts from every process, both foreground and background. To understand the impacts associated with the foreground system we need to find the impacts, both direct and indirect, i.e. from the foreground processes themselves and from the upstream background impacts associated with the foreground processes.

The goal is to find a matrix that aggregates all impacts to the foreground processes. We first find the production output from the foreground processes $\mathbf{x}_{\mathrm{f}}$ 35:

$$\mathbf{x}_{\mathrm{f}} = (\mathbf{I} - \mathbf{A}_{\mathrm{ff}})^{-1}\mathbf{y}_{\mathrm{f}} \tag{35}$$

Next we find the demand put on the background system from the foreground processes $\mathbf{M}_{\mathrm{bf}}$ (36)[4]:

$$\mathbf{M}_{\mathrm{bf}} = \mathbf{A}_{\mathrm{bf}}\hat{\mathbf{x}}_{\mathrm{f}} \tag{36}$$

Next we find the output from each background process associated with the demand from the foreground processes $\mathbf{X}_{\mathrm{bf}}$ (37):

[4] $\hat{\mathbf{x}}_{\mathrm{f}}$ is the matrix with the vector $\mathbf{x}_{\mathrm{f}}$ on the diagonal and zeros elsewhere.

$$\mathbf{X}_{\mathrm{bf}} = (\mathbf{I} - \mathbf{A}_{\mathrm{ff}})^{-1}\mathbf{M}_{\mathrm{bf}} \tag{37}$$

This enables us to find the indirect impacts from the foreground processes generated in the background $\mathbf{D}_{\mathrm{pro,bf}}$ (38):

$$\mathbf{D}_{\mathrm{pro,bf}} = \mathbf{C}\mathbf{S}_{\mathrm{b}}\mathbf{X}_{\mathrm{bf}} \tag{38}$$

Last we need the direct impacts generated internally in the foreground system $\mathbf{D}_{\mathrm{pro,ff}}$ (39):

$$\mathbf{D}_{\mathrm{pro,ff}} = \mathbf{C}\mathbf{S}_{\mathrm{f}}\hat{\mathbf{x}}_{\mathrm{f}} \tag{39}$$

The total impacts from the foreground system $\mathbf{D}_{\mathrm{pro,f}}$ is then the sum of $\mathbf{D}_{\mathrm{pro,bf}}$ and $\mathbf{D}_{\mathrm{pro,ff}}$, i.e. the indirect and the direct impacts (40):

$$\mathbf{D}_{\mathrm{pro,f}} = \mathbf{D}_{\mathrm{pro,bf}} + \mathbf{D}_{\mathrm{pro,ff}} \tag{40}$$

[14]

## 4.6 Allocation

Allocation is how LCA deals with processes producing more than one valuable product, e.g. excess heat produced at an electricity production plant. The issue is how we divide the impacts from one product onto the different sub products, e.g. how much of the impacts that stem from the production of heat and how much from electricity. The subject of allocation might be the most controversial in LCA, because the impacts might differ between different allocation methods [27]. It should be a thorough consideration deciding whether allocation is needed or not, it is preferable to disaggregate the processes in such a way that we understand which co-products instigates the stressors [28].

There are two main methods of allocation that is mainly used in LCA (see litt.review 7), Substitution Method (SM, called system expansion in ISO), and Partitioning Method (PM). In ISO 14044 2006 SM is preferred over PM [17]. Here we will look at the framework of the methods.

First we need to understand the concept of multiple co-products mathematically. The total impact $d$ (scalar value) from a process producing $n$ products for a specific impact category, e.g. GWP, is the sum of the impacts from all the co-products (41):

$$d = \sum_{1}^{n} d_i = \sum_{1}^{n} u_i y_i \tag{41}$$

Where $u_i$ is the unit based impacts from co-product $i$, and $y_i$ is the unit based demand put on the part of the process producing co-product $i$ [27].

### 4.6.1 Partitioning Method

The partitioning method is based on dividing the share of the impacts from a process onto a sub-product based on a chosen parameter, e.g. mass, energy, economic value etc. [14]. The $i$ co-products gets assigned a share value, $\alpha_i$, which is the fraction of the total chosen parameter that stems from co-product $i$, e.g. two co-products from one process has the same mass and mass is the chosen parameter, the $\alpha$-value for both would be 0.5. It follows that the sum of fractions is equal to one (42). Given a total impact $d$ the impacts from co-product $i$ is given by (43) [27]:

$$\sum_{1}^{n} \alpha_i = 1 \tag{42}$$

$$d_i = \alpha_i d \tag{43}$$

It follows from (41) that the unit based impacts for co-product $i$ is given by (44) [27]:

$$u_i = \alpha_i d y_i^{-1} \tag{44}$$

### 4.6.2 Substitution Method

When using this method of allocation to determine the impact from co-products, the practitioner expands the system to include additional products from processes related to the co-products [17]. The system boundary is moved in such a way that alternative products of the same kind is included in the foreground system, the impacts stemming from these alternative products are then subtracted from the total impacts from the process in question and the rest of the impacts is then charged on the main co-product [27].

The main co-product, i.e. the product we want to determine the impacts of is $i = 1$, and $i \neq 1$ are the other co-products. As in (41) the total impacts from a process with $n$ co-products is then given by (45) [27]:

$$d = u_1 y_1 + \sum_2^n u_i y_i \tag{45}$$

Then the unit based impacts $u_i$ from the $n$ processes is substituted by the unit based impacts $u_i^*$ from the product from the alternative process. We must assume that $u_i = u_i^*$, such that the total impacts is given by (46) [27]:

$$d = u_1 y_1 + \sum_2^n u_i^* y_i \tag{46}$$

It follows then that the unit based impacts from the main co-product is given by (47) [27]:

$$u_1 = \left(d - \sum_2^n u_i^* y_i\right) y_i^{-1} \tag{47}$$

# 5 Characterization Factors

In this section we will look at the basic mathematical framework used to calculate the characterization factors (CF) for the most important impact categories, global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and eco-toxicity and human toxicity (ET, HT); each term will be explained. The method used is the ReCiPe method.

## 5.1 Global Warming Potential

Here we will look at the mathematical framework for the CF for the impact category GWP, in ReCiPe called Climate Change, see equation (48):

$$GWP_{x,T} = \frac{\int_0^T a_x \times [x(t)]dt}{\int_0^T a_r \times [r(t)]dt} \tag{48}$$

$GWP_{x,T}$ stands for global warming potential of substance $x$, given in equivalents of substance $r$, in our case, and for most cases in LCA, carbon dioxide. $T$ is the time span considered in the calculation, called time horizon. $a_x$ and $a_r$ is the is the radiative efficiency due to a unit increase in atmospheric abundance of substance $x$ and $r$ respectively. $[x(t)]$ and $[r(t)]$ is the abundance of substance $x$ and $r$ respectively, dependent of time. The numerator and denominator is absolute when viewed on their own, while $GWP_{x,T}$ is the potential of substance $x$ relative to $r$. Different gases can then easily be compared by their value $GWP_{x,T}$. The values may vary depending on what time horizon we are looking at. Gases with longer or shorter life spans compared to $CO_2$ will have very different potentials depending on the time horizon, see figure 6 [19].

## 5.2 Acidification

### Endpoint Characterization Factor

Equation (49) shows the endpoint CF, $CF_{endpoint,x}$, for a given substance $x$:

$$CF_{endpoint,x} = \frac{dSpecies}{dM_x} = SD_{terr} \times \sum_j A_j \times \frac{dDEP_j}{dM_x} \times \frac{dBS_j}{dDEP_j} \times \frac{dPDF_{added}}{dBS_j} \tag{49}$$

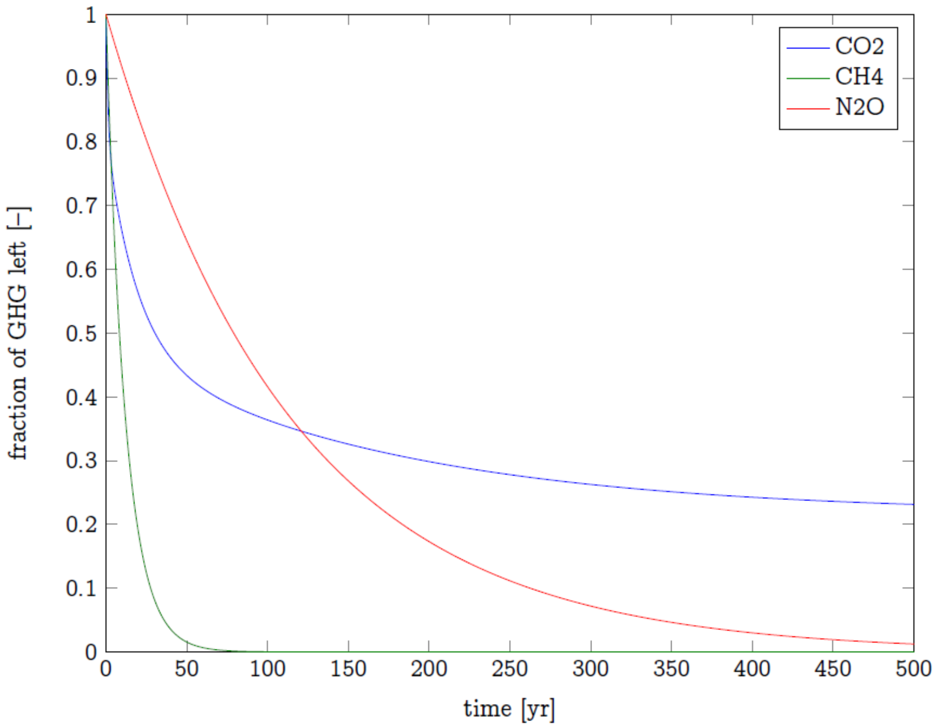


Figure 6: this plot shows the fractions of gas, the y-axis, left after a period of time, the x-axis. F.ex. after 70 years no methane is left, after 500 years almost no nitrous oxide is left and, the carbon dioxide converges to about 20 percent

$CF_{endpoint,x}$ is the endpoint characterization which is a measure of species loss given in [$yr \times kg^{-1}$] for a given forest area j, $A_j$. The characterization factor consists of the species density, area, fate and effect factor, i.e. the last two terms. $SD_{terr}$ is the species density of the area [19].

$dPDF_{added}$ is the marginal change in the added potentially disappeared fraction of species ($PDF_{added}$), while $dBS_j$ is the marginal change in the base saturation ($BS$) in j, i.e. the change in the degree to which the adsorption complex of a soil in is saturated with basic cations, other than hydrogen and aluminum. $dPDF$ divided on $dBS$ is called the effect factor (EF), which is a parameter that relates an exposure level to the effect it has on a species or an ecosystem [29] [19].

$dDEP_j$ is the marginal change in deposition ($DEP$), in the given forest area j, while $dM_x$ is the marginal change in the emissions ($M$) of the given substance $x$. $dDEP/dM_x$ is the atmospheric part of the fate factor (FF), defined as the marginal change in deposition due to an emission of $x$. $dBS_j/dDEP_j$ is the soil part of the fate factor and is the marginal change in $BS_j$ in a forest area j, due to a marginal change in the deposition in forest area j [19].

### Midpoint Characterization Factor

For Midpoint CF only the FF, $dBS_j/dDEP_j$, is important. A location independent FF is created for a substance $x$ by multiplying with area (50):

$$FF_x = \frac{\sum_j (\Delta BS_j \times A_j)}{\Delta M_x} \tag{50}$$

To get the terrestrial AP given in $SO_2$ equivalents we divide by the FF of $SO_2$ (51) [19]:

$$TAP = \frac{FF_x}{FF_{SO_2}} \tag{51}$$

## 5.3 Eutrophication

### 5.3.1 Midpoint Characterization Factor

Here we'll find the CF of eutrophication from the phosphorus and nitrogen transports from agricultural inputs and municipal sewages into the inland waters and coastal seas. Equation (52) shows the fate factor for a given nutrient $x$ in an exposed aquatic system $j$, $FF_x = dC_{x,j}/dM_x$. It's defined as the marginal change in concentration of $x$ in $j$ due to a marginal change in emission rate, the use of units may be arbitrary but are usually $[tn/km^3]$ for the concentration and $[tn/yr]$ for the emission rate, which leads to $[yr/km^3]$ for the fate factor. This method is however only applicable if the nutrient is emitted directly into the water compartment. If the nutrients are dispersed as either fertilizer or manure the (categorized as $i$ in (52)), the fate is evaluated as the mass of either, to the soil. The concentrations are normalized with respect to affected water area and its impact on the marine systems; it gives the following final fate factor equation, where $A$ is the water area of system $j$, and $k$ is to discriminate between the inland water and the sea.

$$FF_k^x = \frac{\frac{1}{\sum_j A_j^k} \times \sum_j dC_{x,j}^k \times A_j^k}{dM_{x,i}} \tag{52}$$

We use the FF to find the midpoint characterization factor. We discriminate between coastal seas and inland freshwaters, a reason for doing so is that the limiting growth factor for the two is different, nitrogen for coastal waters and phosphorus for inland, and we treat these two as separate subcategories. The midpoint CF are for seawater the FF for nitrogen, and the CF for freshwater is the FF for phosphorus [19].

### 5.3.2 Endpoint Characterization Factor

To find the endpoint CF we need to find how much damage the increase of the nutrients have on species, i.e. species loss. If we find this damage factor we can use together with the midpoint CF to find the endpoint CF. We find the damage factor we plot the potentially disappeared fraction $PDA$ as a function of the concentration of the nutrient in the water. We then take the range of the nutrient concentration for the given water area, e.g. the European freshwaters, the damage factor is then the slope over the given area. To find the endpoint CF we multiply the midpoint CF and the damage factor. This will give us a endpoint CF with unit $[PDF.yr/tn]$ which can then be converted to $[species.yr/tn]$ [19].

## 5.4 Toxicity

Here we will look at the mathematical framework for finding the fate, effect, damage and characterization factors for human and eco-toxicity. The CF are functions of the aforementioned factors.

### Fate Factors

The FF used in eco-toxicity is shown in equation (53), and stands for the transport efficiency of substance $x$ from compartment $i$ to compartment $j$, $[yr.m^{-3}]$:

$$F_{j,i,x} = \frac{\delta C_{j,x}}{\delta M_{i,x}} \tag{53}$$

The numerator is the marginal change in the concentration of substance $x$ from compartment $j$, in units of $[kg.m^{-3}]$, while the denominator is the marginal change in the emission of substance $x$ to compartment $i$, $[kg.yr^{-1}]$.

For HT another FF is used and is shown in equation (54), it stands for the human population intake fraction at geographical scale $g$, accounting for transport of substance $x$ via intake route $r$ from emission compartment $i$ $[-]$:

$$iF_{j,i,x} = \frac{\delta I_{r,x,g}}{\delta M_{i,x}} = \frac{\delta I_{r,x,g}}{\delta C_{j,x}} \times \frac{\delta C_{j,x}}{\delta M_{i,x}} \tag{54}$$

$\delta I_{r,x,g}$ is the marginal change in intake of substance $x$ by human population via intake route $r$ at scale $g$ in $[kg.day^{-1}]$ [19].

### 5.4.1 Damage & Effect Factors

The EF for ET of substance $x$ in compartment $j$ is shown in equation (55):

$$E_{j,x} = \frac{\delta PDF_{tox}}{\delta C_x} \tag{55}$$

Where the numerator is the marginal change in potentially disappeared fraction of species, while the denominator is the marginal change in the environmental concentration of substance $x$.

The combined human effect and damage factor for substance $x$ via intake route $r$ in terms of loss and disability of life years per kg of intake for carcinogenic or non-carcinogenic effect, in $[yrlost.kg^{-1}]$ is shown in equation (56):

$$E_{r,x,c} = \frac{\delta DALY_e}{\delta R_e} \times \frac{\delta R_e}{\delta TU_e} \times \frac{\delta TU_e}{\delta I_{r,x}} \tag{56}$$

$\delta DALY_e$ is the marginal change in sum of years of life lost $YLL_e$ and, years of life disabled, $YLD_e$ caused by disease type $e$. $\delta R_e$ is the marginal change in chance of disease type $e$ occurring. $\delta TU_e$ is the effective toxicity of the pollutant [19].

### 5.4.2 Characterization Factors

The CF for ET is the product of the FF and the EF, for substance $x$ emitted to $i$ and transported to j in $[yr.kg^{-1}]$ (57):

$$CF_{j,i,x} = F_{j,i,x} \times E_{j,x} \tag{57}$$

To find the environment-specific CF for substance $x$ emitted to compartment $i$ causing effects in environment $q$ we use equation (58):

$$CF_{q,i,x} = SD_q \times \sum_j CF_{j,i,x} \times W_{j\epsilon q} \tag{58}$$

$SD_q$ is the species density in $q$, while $W_{j\epsilon q}$ is the area or the volume of compartment $j$ in $q$.

The endpoint CF for the HT is the product of the FF and the combined EF and damage factor, for effects in scale $g$ for substance $x$ from compartment $i$ via route $r$, in $[yr.kg^{-1}]$, see equation (59):

$$CF_{r,i,x,g,c/nc} = F_{r,i,x,g} \times E_{r,x,c/nc} \tag{59}$$

The midpoint CF for HT is shown in equation (60), difference is that the stage that calculates loss is gone [19]:

$$CF_{r,x,c/nc} = F_{r,i,x,g} \times \frac{\delta TU_e}{\delta I_{r,x}} \tag{60}$$

## 5.5 Three Ways to Model Characterization

The uncertainty of the characterization models are source for discuss. We divide different sources of uncertainty and choices of modeling into three perspectives, the individualist, the hierarchist and the egalitarian. Here we'll see how each of the perspectives handles the global warming, acidification and toxicity categories.

### 5.5.1 Individualist

The Individualist bases his choices on short term interest, uses impact types that are undisputed, he thinks that humans can adapt by use of technology. Regarding AP and GWP the individualist only feels the near future is important, and therefore a time horizon of 20 years is used. Regarding toxicity a time horizon of 100 years is used, and he considers only intake routes via air and drinking water. In marine ET the oceanic environment in the calculations for essential metals is excluded, and only substances with strong evidence of carcinogenity is included. When calculating the damage to humans YLL was used in stead of disability adjusted life years (DALY). A minimum number of four species was used, while the two other scenarios had no minimum number [19].

## 5.6 Hierarchist

The hierarchist conforms to the rules, and uses the most commonly accepted policies. Regarding AP and GWP the hierarchist thinks there are no scientific reason for choosing a specific time scale, therefore a time horizon of 100 years is used, the same is true for toxicity. All intake routes for human consumption is considered. In marine ET the sea and oceanic compartments in the calculation of the marine eco-toxicological impacts is included. Substances that don't have sufficient evidence of carcinogens but is suspected to be harmful are also included. When calculating the damage to humans DALY is used. No minimum number of species was used [19].

## 5.7 Egalitarian

The egalitarian is the most precautious type, and uses the longest time frames. Regarding AP and GWP the egalitarian perspective states that all generations from now and forward is equally weighted, therefore a time horizon of 500 years is chosen. The egalitarian might even want to use a even longer life span than 500 years, but for GWP the atmospheric lifetime of the substances are usually shorter than 500 years. Regarding TP the same time horizon is chosen. All intake routes for human consumption is considered. In marine ET the sea and oceanic compartments in the calculation of the marine ecotoxicological impacts is included. Substances that don't have sufficient evidence of carcinogens but is suspected to be harmful are also included. When calculating the damage to humans DALY is used. No minimum number of species was used [19].

# 6 Life Cycle Interpretation

The last phase in LCA is as the name might suggest the interpretation of the results, and drawing conclusions based upon them. ISO14044 states that the life cycle interpretation phase of an LCA should contain identification of significant issues bases on the LCI and LCIA phases of the LCA. It should contain an evaluation regarding completeness, sensitivity and consistency, and lastly it should contain conclusions, recommendations and any limitations of the study [17].

Inventory and impact assessment must be checked for completeness and consistency. This is done by checking the inventory for gaps in the data collected, and by checking the methodological choices used in the study, i.e. checking how changes in methodology may change the results. Uncertainty of data should also be checked, seeing that some data might be just estimates. This might be done by seeing how changing the data within the uncertainty range would effect the results. Critical data should also be checked for sensitivity by the same method. For example taking the most critical data and seeing how a plus/minus percentage increase would effect the results.

The phase handles how we present the results, this can be done many ways and is much up to the practitioner. Highlighting the stressors, resources or phases that contribute most to the environmental impacts is one way to emphasize key aspects of the results. For example for the production, use and demolition of a electric car it's interesting to know which phase that contribute the most. How presentation is done is all dependent on the intended audience, and how the results pen out.

# 7 Literature Review

In this section we will look at what methodologies have been used in earlier studies on aquaculture. The focus will mainly be on eleven studies on farmed fish, from 2006 till today; highlighting methodological choices as, functional unit, system boundary, data, impact categories, LCIA method, allocation and interpretation. Results from the studies will not be covered, seeing that the main focus of this paper is LCA methodology. The reason for researching these studies is to get an overview of the state of the art of the methodology used in LCAs on aquaculture, forming the basis for methodological choices during the LCA in the Master's Thesis.

The studies were found using the scopus database, and google scholar. The choice of studies were not far from exhaustive, choosing studies that were written by renown LCA practitioners.

## 7.1 Results

### 7.1.1 Functional Unit

The functional unit is the quantified performance of a product system for use as a reference unit to which the inputs and outputs are normalized. It has to be clearly defined and measurable [30] [17]. The functional unit is also described in 2.2.1.

The most common functional unit used in the LCA's reviewed are one live weight tonne of fish at farm gate and slaughtering, six studies. Two used one kilogram of fish to market, two used one tonne to marked, and one used 200 gram fillets to market. See table 1.

Grönros et al. 2006 [31] used one tonne ungutted fish after slaughtering to avoid allocation of the remains . Iribarren et al. 2010 [32], Ellingsen et al. 2006 [13], Ziegler et al. 2013 [33], Pelletier et al. 2010 [34] and Mungkung et al. 2013 [35] all used consumption ready fish to market. Using a smaller size for the functional unit like one kilogram, will make the results more relatable to costumers and clients. Ellingsen et al. 2006 [13] used a 200 gram fillet, this would put the results in perspective right from the start seeing that 200 gram fillets is a standard protein size for meals.

Samuel-Fitwia et al. 2013 [36], Aubin et al. 2009 [37], d'Orbcastel et al. 2009 [38], Pelletier et al. 2009 [12] and Ayer et. al 2009 [39] all use live weight fish, and all are comparative LCA's, i.e. they are comparing different systems or products. Comparative LCA's must take into account the differences between the products, and a functional unit that describes the performance of all the products equally should be chosen [16, p. 46].

### 7.1.2 System Boundaries

System boundaries are a set of criteria specifying which processes are part of the product system [28], see 2.2.2 for description of system boundaries.

The most common boundary cut off are at farm gate, 6 of 11 studies, i.e. only including processes up to the end of grow out. The second most common system boundary are at market, 4 of 11 studies, i.e. reaching sale. Only Iribarren et al. 2010 [32] considered the whole production system also including the processing, marketing and transport to costumer, and found that a large part of the impacts from the mussel system stems from processes after farm gate. The choice of system boundary have to be consistent with the goal of the study [17]. For example Ziegler et al. 2013 [33] includes packaging and transport to market for all species in the study, the goal of the study was to discover the total impacts, and it was therefore important to include the processes after farm gate. Ayer et al. 2009 [39] had the goal of comparing different production systems, and therefore chose system boundary at farm gate; this because the processes after the farm gate would be the same for the different cases in the study. A problem by choosing to exclude the processes after farm gate might be if the study is used in a different way than intended, e.g. comparative studies with system boundaries at farm gate do not show total impacts, they only compare the different cases up to the farm gate.

Whether or not to include construction and demolition of infrastructure also has to do with the goal of the study. Ziegler et al. 2013 [33] includes infrastructure for the same reason as stated earlier, the goal being to find the total impacts. Pelletier et al. 2009 [12] excludes infrastructure, citing that earlier studies shows them to be negligible. Samuel-Fitwia et al. 2013 [36], Pelletier et al. 2010 [34] and Pelletier et al. 2009 [12] all excluded infrastructure from their studies. Samuel-Fitwia et al. 2013 [36] do not give any reason for excluding infrastructure, and also excludes use of antibiotics and sanitizing chemicals.

### 7.1.3 Data

The studies ranges from single farms, e.g. d'Orbcastel et al. 2009 [38], to nation wide studies, e.g. Pelletier et al. 2009 [12]. Data from such different studies will therefore be dependent on quality of book keeping at the different locations and the thoroughness of the LCA practitioner. For example Ayer et al. 2009 [39] used data directly from the studied facility and from interviews with the manager, while Pelletier et al. 2009 [12] used data from several companies and compiled them into region wide averages. The available data from the studies were lacking for most of the studies making rechecking and retracing of the methods and procedures used impossible. Grönroos et al. published the results from the life cycle inventory in 2003 [40], making it possible to recheck and review their work. ISO [17] states that the quality of data, should include possibility of reproducing the studies; Grönroos' way of handling the data is way of keeping the journal article compact while still maintaining transparency and reproducibility.

All but Grönros et al. 2006 [31] used Simapro LCA software, Grönros used KLC-ECO software. Simapro is a LCA software tool for structuring and analyzing data to find the environmental impacts of products and services across all life cycle stages. The most commonly used version of Simapro, v.7, comes with the background databases Ecoinvent, US LCI, European Life Cycle Data, US Input Output, EU and Danish Input Output, Zwiss Input Output, LCA Food, and Industry Data v.2 [41]. Ecoinvent was used in six studies, and its likely that two more also used it due to its inclusion in Simapro. Ecoinvent is a background LCI database. It contains international datasets in areas of energy, transport, contruction materials, chemicals etc. [18]. Two studies used more than one database for their background data. What background data sources the different studies used remains unclear for most of the studies. Some of the databases used were also rather old, e.g. Franklin, LCA Food, IDEMAT2001, ETH-ESU 96, and BUWAL250, making the results from the studies less strong than they would be if the background databases were up to date.

Table 1: Table of methodology found in litterature review

| Authors | Year | Species | Functional unit | System boundary | Allocation method | Software | Background databases |
|---|---|---|---|---|---|---|---|
| Fitwia et al. | 2013 | Rainbow trout | 1 tonne of live fish | Farm gate | System expansion | Simapro 7.2 | n/a |
| Mungkung et al. | 2013 | Carp and Tilapia | 1 tonne of live fish | Market | Partition by economic value | n/a | Ecoinvent |
| Ziegler et al. | 2012 | Salmon, mussels, cod, saithe, haddock, herring and mackerel | 1 kg of edible seafood | Market | Partition by mass | Simapro 7.2 | Ecoinvent |
| Iribarren et al. | 2010 | Mussels | 1 kg of frozen or canned mussel | Costumer | System expansion | Simapro 7 | Ecoinvent |
| Pelletier et al. | 2010 | Tilapia | 1 tonne of tilapia | Market | Partitioning by gross energy content | Simapro 7.1 | Ecoinvent |
| Aubin et al. | 2009 | Rainbow trout, sea bass and turbot | 1 tonne of live fish | Farm gate | n/a | Simapro 6 | n/a |
| Ayer et al. | 2009 | Salmonoids | 1 tonne of live fish | Farm gate | Partitioning by gross energy content | Simapro 7.0 | Ecoinvent, Franklin, LCA Food and IDE-MAT2001 |
| d'Orbcastel et al. | 2009 | Trout | 1 tonne of live fish | Farm gate | n/a | Simapro 6.1 | CML2001 |
| Pelletier et al. | 2009 | Salmon | 1 tonne of live fish | Farm gate | Partitioning by gross energy content | Simapro 7.1 | Ecoinvent |
| Ellingsen et al. | 2006 | Salmon, cod(fished) and chicken | 200 gram fillets | Market | Partition by mass used on cod, economic on salmon | Simapro | ETH-ESU 96 and BUWAL250 |
| Grönroos et al. | 2006 | Rainbow trout | 1 tonne ungutted | Farm gate | Not needed | KLC-eco | n/a |

### 7.1.4 Impact Assessment Methods, Impact Categories

A wide range of impact categories were used in the eleven studies. Some are overlapping like eutrophication potential with terrestrial eutrophication potential and aquatic eutrophication potential; and eco-toxicity with terrestrial eco-toxicity potential, fresh water aquatic eco-toxicity potential and Marine toxicity potential; making it harder to directly compare the results from the studies. All studies included global warming potential as an impact category, unsurprising seeing the focus on climate change in the community all over the world. Acidificaton potential was included in all studies except from Ziegler et al. 2012 [33]. Eutrophication potential in one form or another was inluded by all but Ziegler et al. 2012 [33], Ayer et al. 2009 [39], and Aubin et al. [37]. Seven of the studies included energy demand as a category, in step with the goal of the studies. A full view of the categories used is shown in table 1.

The most commonly used characterization methodology is the CML method, used in seven of the studies. Ziegler et al. 2012 [33] only stated that the method used was according to ISO methodology. Ellingsen et al. 2006 [13] used Ecoindicator 99, and was the only endpoint characterization method used. Two of the studies didn't mention what methodology they used.

### 7.1.5 Allocation

See chapter 4.6 on allocation for more in depth theory on the subject. A few different methods of dealing with allocation was used in the studies. Three studies used partitioning by gross nutritional energy content, two used partitioning by mass, two used partitioning by economic value, two used system expansion to avoid allocation by partitioning, one avoided allocation by using ungutted fish as functional unit, and one used partitioning by both mass and economic value. Ziegler et al. 2012 [33] used mass allocation, and stated that after much discussion they landed on it after they couldn't find a way of using system expansion (as recomended in ISO [17]), they considered using economic value but found it unsuitable due to variability caused by variation in market prices. Gross energy content allocation was also not chosen because of higher burdens on cod liver due to high fat content. The same was found by Svanes et al. 2011 [42], economic allocation might be good for internal improvement work, say within a company, but is not suitable for performance tracking. While mass allocation is insensitive to changes in market.

Table 2: Table of impact categories used

| Category | Abr. | Fitwia | Mungkung | Ziegler | Iribarren | Pelletier10 | Aubin | Ayer | d'Orbcastel | Pelletier09 | Ellingsen | Grönroos |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming potential | GWP | X | X | X | X | X | X | X | X | X | X | X |
| Acidification potential | AP | X | X | | X | X | X | X | X | X | X | X |
| Eutrophication potential | EP | X | X | | X | X | X | | | X | X | |
| Terrestic eutrophication potential | TEP | | | | | | | | | | | X |
| Aquatic eutrophication potential | AEP | | | | | | | | | | | X |
| Fossil fuel depletion | FD | | | | | | | | | | X | X |
| Tropospheric ozon formation | TOF | | | | | | | | | | | X |
| Abiotic depletion potential | ADP | | | | X | | | X | | | | |
| Human toxicity potential | HTP | | | | X | | | X | | | | |
| Marine toxicity potential | MTP | | | | X | | | X | | | | |
| Culmative energy demand | CED | | X | | | X | X | X | X | X | | |
| Ozon layer depletion | ODP | | | | X | | | | | | | |
| Photochemical oxidant formation | POFP | | | | X | | | | | | | |
| Fresh water aquatic eco-toxicity potential | FETP | | | | X | | | | | | | |
| Terrestrial eco-toxicity potential | TETP | | | | X | | | | | | | |
| Biotic resource use | BRU | | | | | X | | | | X | | |
| Net Primary Production Use | NPPU | | X | | | | X | | X | | | |
| Water dependence | WD | | X | | | | X | | X | | | |
| Land competition | LC | X | X | | | | | | | | | |
| Surface use | SU | | | | | | | | X | | | |
| Eco-toxicity | ET | | | | | | | | | | X | |
| Carcinogens | C | | | | | | | | | | X | |
| Resp. Inorganics | RI | | | | | | | | | | X | |

### 7.1.6 Interpretation

See 6 on life cycle interpretation. ISO states that the life cycle interpretation phase of an LCA should contain identification of significant issues bases on the life cycle inventory and life cycle impact assessment phases of the LCA. It should contain an evaluation regarding completeness, sensitivity and consistency, and lastly it should contain conclusions, recommendations and any limitations of the study [17]. Most studies conducted sensitivity studies, assessing the reliability of the results by determining how they were affected by uncertainties in the data, allocation methods etc. For example Ayer et al. 2009 [39] did a sensitivity analysis comparing economic allocation versus mass allocation. While Ellingsen et al. 2006 [13] used two different impact assessment methods by using both Eco-indicator 95 and EDIP indicator to illustrate the sensitivities of the conclusions in the study.

# 8 Draft of Goal and Scope

In this section I will start on the goal and scope part of the study. I will propose what methodology to use, i.e. functional unit, impact assessment method, background database, system boundary and impact categories. It must be stated that the choices made in this paper is not set in stone, and is up for revision next year when I'm working on the Master thesis.

## 8.1 Goal

The goal of the study is as stated in the introduction to compare a closed marine aquaculture system with an open cage system normally used today. The goal is to highlight differences in environmental impacts and to find spots in the production that contribute the most to environmental impacts. The closed system that will be used as reference is a fish farm in Brønnøysund where a new concept design for closed sea cages is being developed, this system is described in the introduction, section 1.

As pointed out in the introduction the key differences in the design compared with the open system are use a bag in stead of a net, the use of power for pumping water into the bag, and use of oxygen or production of oxygen for oxygenating the water inside the bag. Another big change is that both dead fish and sediments gets pumped to the surface, meaning lesser local emissions of waste. If there is a difference in the smolt phase, e.g. if the closed system have less mortality in the early life stage, it should be investigated seeing that the smolt phase is a energy heavy phase of the production, and making it more effective would surely decrease the impacts.

## 8.2 Scope

### 8.2.1 System Boundary

As this is a comparative study the total impacts from cradle to grave aren't as important as is finding the differences between the systems. Both the closed and the open system have the same system boundary, see figure 7. The processes included are smolt production, feed production, infrastructure construction and the fish farm. The infrastructure construction process might be neglected due to low impacts stemming from the phase in similar studies, see section 7.1.2 for more on this. As seen in the figure the system boundary is at farm gate, which is the most commonly used system boundary, see 7.1.2. By doing this we don't need to model the processes like slaughtering and transport to market, seeing that those processes are identical for both the closed and open system. We also don't need use allocation on the fish in this case when the fish is still in one piece and is seen as one product. Had we had the system boundary at market we would have had to allocate the different coproducts of the fish, e.g. the fillet and the guts. This was similarly done by Grönros et al. 2006 [31], avoiding allocation by using ungutted fish as functional unit. Allocation might be needed when dealing with the waste collected from the fish farm. If the sediments from the fish cage can be used as say for example fertilizer, we may use system expansion to exclude the impacts from the production of the same amount of fertilizer from the study, see section on 4.6.2 on allocation for how this is done.

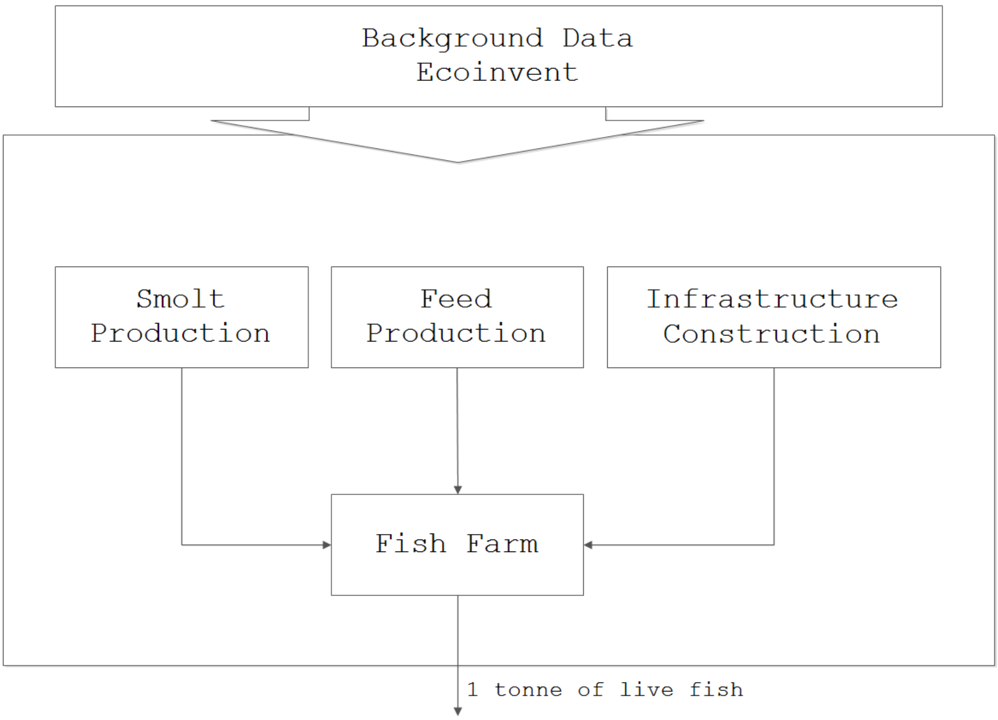


Figure 7: system boundary used in the study

### 8.2.2 Functional Unit

Seeing as the system boundary is at farm gate a functional unit of 1 tonne of live fish is appropriate. This was used in 6 of 11 studies reviewed in the literature review. Choosing a commonly used functional unit makes it easier to compare the results with similar studies, 1 tonne is also easy to scale.

### 8.2.3 Software and Background Database

The choice of LCA software is one of preference more than a methodological choice. Simapro is by far the most used LCA software, but that does not mean it's better than any other software, the cogs running in the background of the software are the same. Professor Anders Stømman recommended that I use the internally developed LCA software Arda. Arda uses the ReCiPe method and has the Ecoinvent database integrated. Ecoinvent is regarded as the best background database for European use [14]. It contains data on energy supply, fuels, materials, transport etc. Arda can also choose what characterization perspective to use.

The impact categories that will be included are all categories from the ReCiPe method, see section 2.2.3 on what categories that are included.

# 9 Future Work

Next comes the work on the LCI phase, collecting data and structuring it to be used in the LCIA. A form is sent to Aquafuture to start collection of the data. We also need to come in contact with a company that can help with data on the open system, maybe Sinkaberg Hansen could help seeing they are in cooporation with Aquafuture; the same regarding the smolt and feed production.

Regarding allocation, the sedimented waste from the closed system needs to be allocated to highlight the difference between the two systems. We need to find out what needs to be done to make it viable for fertilizing, or if it's just waste. It also rises the question of local direct emissions at the farms, how large are they and can they be neglected?

Contact have been made with the fish farming company Sinkaberg Hansen, and they have agreed to provide information on the open reference system and the smolt system. I have also contacted Skretting, and they have agreed to help on the feed modeling and inventory part.

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