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A Comparative Life Cycle Assessment of Conventional and All-Electric Car Ferries

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Marine Technology
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MASTER THESIS IN MARINE TECHNOLOGY

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For stud.techn.

Annelise Berentsen Kullmann

A Comparative Life Cycle Assessment of Conventional and All-Electric Car Ferries

Background
Increasing awareness of climate change is emerging and the marine transport sector is exposed to more demanding regulations to reduce impacts. In Norway the government have targeted car ferries to reduce the emittance of greenhouse gasses from the domestic transport sector. The car ferry fleet in Norway is also aging and many ferries are up for renewal the next years. Some studies conducted by companies with commercial interests in the ferry market, confirm that all-electric car ferries have less impacts on global warming than conventional ferries driven on marine diesel oil. The challenge with most of these studies is the lack of clear methodology or inaccessible data and calculations.

Objective
The desired outcome of this thesis is to compare the environmental benefits and burdens associated with using all-electric ferries with conventional alternatives. A comparative life cycle assessment (LCA) will therefore be carried out on the all-electric ferry MS Ampere and the diesel-driven MF Oppedal. Both ferries are serving the same ferry-route across the Sognefjord between Lavik and Oppedal. In addition, two theoretical cases are studied where MS Ampere has a propulsion system driven on liquefied natural gas and diesel. LCA quantifies several environmental impacts, including climate change and it is one of the most developed methods used in environmental assessments. The analysis is considered novel and it is therefore desired to provide a basis, and accessible data, for future studies.

Tasks
The candidate is recommended to cover the following parts in the master thesis:

a. Review state of art within the topic. That means to document what others have done and published previously.
b. Find similar studies that have been conducted in order to find and define the methodology to be used.
c. Carry out a simplified LCA consisting of:
   - Clear and concise goal and scope definition
   - Data collection and inventory analysis
   - Impact assessment
   - Interpretation of results

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General
In the thesis the candidate shall present her personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable
- The thesis shall be submitted in two (2) copies:
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Sub-supervisor: Svein Aanond Aanondsen

Company contact: -

Deadline: 17.06.2016

Preface

This master thesis represents the completion of my M.Sc. degree within Marine Design and Logistics at the department of Marine Technology, Norwegian University of Science and Technology. It is written during the spring semester of 2016 entirely by Annelise Berentsen Kullmann, in this report referred to as the researcher. The thesis is written for audience with background in science or engineering, but most topics are explained from a quite basic level.

I was insecure when outlining the topic of this thesis but after studying environmental impacts from all-electric ferries I have realized it ties my interests in science and technology well together. All-electric propulsion and especially ferries have gotten notable media coverage the last year, making this thesis relevant and an input to more diverse research on all-electric ferries and their environmental impacts.

I would like to thank my supervisors Professor Bjørn Egil Asbjørnslett and Assistant Professor Svein Aanond Aanondsen for help with my work. In addition PhD candidate Linda Ager-Wick Ellingsen has provided data on battery production and helped scaling these. Researcher Evert Bouman has been of considerable help in LCA methodology and modelling. I would also like to thank Professor Sverre Steen and Professor Eilif Pedersen for being available for my questions. The Chief technology officer at Norled, Sigvald Breivik, and the sales manager at Fjellstrand, Edmund Tolo have also provided information this thesis had been incomplete without.

My family and friends have also supported me through the completion of this master degree, and a special thank you is directed to the ones who proofread the report before delivery.

Annelise Berentsen Kullmann

Tyholt, Trondheim 15/6-2016

Abstract

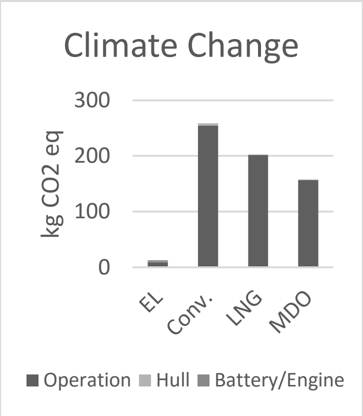
Increased environmental focus in the marine transport sector, and especially focus on its effect on global warming, have initiated the deployment of all-electric propulsion. This thesis quantifies the environmental impacts of four ferry alternatives using the method of life cycle assessment (LCA). An all-electric lightweight catamaran in aluminium is compared to a conventional diesel powered monohull in steel. In addition, two theoretical cases are included where the design is the same as the all-electric ferry but the energy carrier is liquefied natural gas (LNG) or marine diesel oil (MDO).

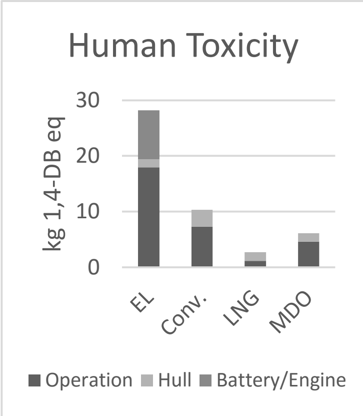
The objective of this thesis is to acquire insights to environmental savings and burdens associated with all-electric ferries and to identify where the largest improvements can be made. This is analysed by performing a comparative LCA on the four cases mentioned. Current studies within the field are somewhat incomplete, and it is therefore strived to establish a transparent dataset to improve the basis for future studies. In Norway the domestic car ferry fleet is also aging and many of them will be replaced when new tender demands are set.

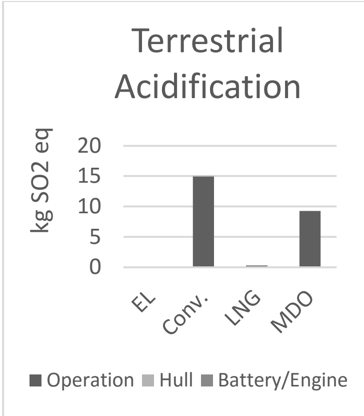
A specific ferry route and two ferry designs were chosen as the basis for the analysis. MS Ampere, the world's first all-electric car ferry operating a ferry route across the Sognefjord in Western Norway, were one of the designs used. MF Oppedal is operating the same ferry route and were the second design used in the analysis.

In the study the impacts are calculated using the ReCiPe characterization method. The impacts are grouped in 18 different categories, linked to different environmental problems or public concerns, called mid-point indicators. Three perspectives are used: egalitarian, hierarchist and individualist. The egalitarian represents a long term, careful and argument-based view. Individualists are looking at short-term and require indisputable cause and effect relations in order to take actions. Hierarchists are somewhere in between, being risk neutral and looking at an intermediate time horizon.

Results in three impact categories global warming potential, human toxicity and terrestrial acidification are presented for the hierarchist viewpoint. This is a selection of three impact categories to illustrate the methodology. The educational software Arda Gui, version 1.8.1 has been used to perform the impact calculations. Impacts are divided in the processes battery/engine, hull and operation. The all-electric ferry is run on the average Norwegian electricity supply mix modelled in the Ecoinvent 2,2 database.







The full set of results have impact categories concerning land use, resource depletion, different toxicity impacts, eutrophication, radiation, ozone depletion, particulate matter formation and photochemical oxidant formation. Different units for a typical pollutant or attribute relevant to the environmental issue or public concern are the measure in each impact category.

The all-electric ferry outperforms the conventional alternatives in impact categories linked to combustive stressors and fossil fuels. Such impact categories are climate change, photochemical oxidant formation, ozone depletion, particulate matter formation and fossil fuel depletion. The all-electric and LNG ferry are significantly better than the ferries run on MDO when considering terrestrial acidification. This is due to the fact that there is no sulphur in the fuel. The electrical ferry has larger impact in all categories concerning toxicity except for the terrestrial ecotoxicity.

A sensitivity analysis of important parameters were performed to investigate the dependency between input and results. Electricity mix, metal used for hull and engines, the number of trips per lifetime and battery life were the parameters varied. The results prove to be sensitive to the electricity mix used. In addition the metal used for hull and engines had impact for the category metal depletion.

The analysis identifies that using all-electric ferries gives a problem shift with reducing impacts in categories linked to combustive stressors and fossil fuels and increasing impacts in toxicity. Similar tendencies have been presented in studies on electrical cars. Extraction of copper as input to the electricity grid and battery contribute largely in the toxicity categories. This makes the results highly dependent on the modelling of background processes such as electricity. The choice of processes can therefore be a source of inaccuracy. Further work should include more emission reducing technologies as well as more complete parts of the ferries, being their components, production, operation and end of life.

Sammendrag

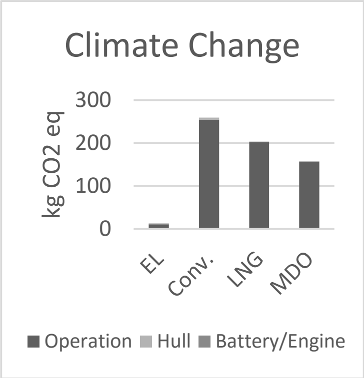
Den marine transportsektoren får globalt stadig strengere utslippsreglement, og det er spesielt mye fokus på utslipp av SO_x og NO_x, og energieffektivitet. Den norske regjeringen har spesiellt fokus på å redusere utslippene av drivhusgasser. I innenriks transport er bilferger et av satsningsområdene. Den norke bilfergeflåten er også aldrende og mange ferger vil bli byttet ut når nye anbudskrav kommer. Både verdens første bilferge drevet på flytende naturgass og bilferge drevet på batteri er blitt tatt i bruk i henholdsvis år 2000 og 2015.

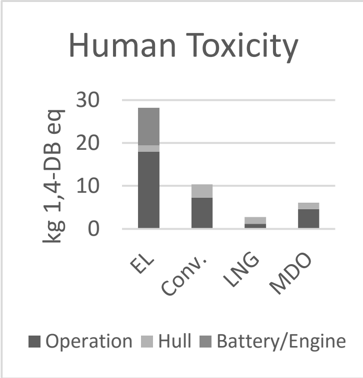
Målet med oppgaven er å sammenlikne miljøpåvirkningene til en elektrisk ferge med konvensjonelle fergealternativer. Metoden som benyttes er livssyklusanalyse(LCA), med ReCiPe karakteriseringsmetode er metoden som benyttes. MS Ampere er batterifergen som trafikkerer fergestrekket mellom Lavik og Oppedal over Sognefjorden på Norges vestkyst. Informasjon fra denne fergen og dens infrastruktur er benyttet i analysen, i tillegg et «konvensjonelt» design som benytter diesel. To teoretiske fergealternativer er også lagt til. Disse er versjoner av MS Ampere som er drevet av diesel og flytende naturgass.

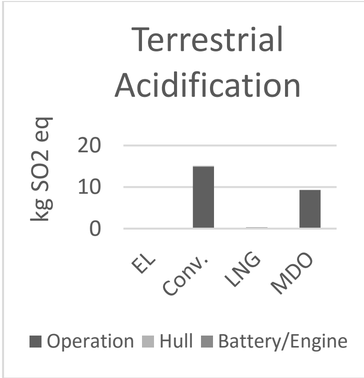
MS Ampere er en katmaran bygget i aluminium for å spare vekt, og skrogdesignet er optimert for å gi lav motstand. Det konvensjonelle designet MS Ampere skal sammenliknes med er MF Oppedal, et enkeltskrog i stål drevet på diesel, som også betjener samme strekning. De to teoretiske alternativene er lagt til for å isolere drivstoff og maskineriløsning. Det finnes studier som har sammenliknet MS Ampere med et konvensjonelt alternativ, men få av disse er klare på metoden som benyttes. I tillegg er tilgangen på informasjon og utførte beregninger begrenset. Resultatene som er gitt omhandler også kun global oppvarming.

Dataprogramet Arda Gui 1.8.1., er benyttet for matematiske bergeninger. Programmet er utviklet ved program for industriell økologi under institutt for energi og prosessteknikk ved Norges teknisk-naturvitenskapelige universitet.Tilgang til fullstendige prosessbeskrivelser for de benyttede databasene har vært begrenset. Dette kan ses på som en eventuell feilkilde.

Resultatene er gitt i 18 miljøpåvirkningskategorier benyttet i karakteriseringsmetoden ReCiPe, og de er koblet til hver sin miljøkonsekvens eller interesseområde. Under presenteres tre av disse kategoriene for de fire fergealternativene. Disse resultatene er et utvalg for å beskrive metoden som er benyttet. En av hensiktene med oppgaven er å presentere flere miljøpåvirkninger for å få et fullstendig bilde som mulig.







I tillegg til global oppvarming, menneskelig giftighet og kontinental forsuring benyttes kategorier om bruk av land, resurser, giftighet, eutrofiering, stråling, nedbryting av ozonlaget, svevestøv og danense av bakkenær ozon. Hver kategori benytter et typisk stoff eller enhet som måleenhet, for eksempel CO_2 for global oppvarming og m^2 for benyttelse av ulike typer landskap. Miljøpåvirkningene kan ses på med tre perspektiv: Individualistisk, hierarkisk og egalitært. Det individualistiske perspektivet har kort tidsperspektiv og krever beviste årsak-virkning sammenhenger for at noe skal tas hensyn til. Et egalitært perspektiv har et langtidsperspektiv og vil ta hensyn ved mistanke om virkning skyldt en årsak, mens det hierarkiske perspektivet ser på et middels langt tidsperspektiv og er risikonøytralt. Resultatene presentert over benytter et hierarkisk perspektiv. Elektrisiteten batterifergen benytter er norsk forsynings elektrisitetsmiks hentet fra Ecoinvent databasen.

Resultatene likner på tilsvarende analyser gjort på elektriske biler. Kategorier som kan kobles til bruk av fossile brensler får mindre påvirkning av en elektrisk ferge enn ferger drevet på fossilt brensel. I de fleste av kategoriene som har med giftighet å gjøre gir det elektriske alternativet en økning sammenliknet med fergene drevet på fossilt brensel. Dette skyldes mest materialinput, utvilling av kobber, til strømnettet og noe material til batteriet.

Det ble utført en sensitivitetsanalyse for å se om elektrisitetsmiks, metall benyttet til skrog og motorer, antall turer i løpet av operasjonstiden og batteriets levetid. Elektrisitetsmiksen menyttet hadde stor påvirkning på resultatet, mens metallet benyttet til skrog og motorer hadde størst påvirkning på utnyttelse av metallresurser.

Analysen har identifisert at elektriske ferger gir reduserte miljøpåvikrninger i kategorier relatert til benyttelse av fossilt brensel og økte miljøpåvikninger i de fleste kategorier for giftighet. Bidrag til økt giftighet kommer hovedsakelig fra utvinnelsen av kobber som skal benyttes i elektristetsnettet. Resultatene er derfor svært avhengige av hvordan bakgrunnsporsessene som elektristet er modellert i databasen som benyttes. Videre arbeid burde inkludere flere utslippseduserende tiltak som for eksempel scrubbere og hydrogen som brensel. Det burde også inkluderes flere deler av produksjon og operasjon av fergene og avfallshåndtering som ikke er inkludert i denne analysen.

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Nomenclature

LCA – Life cycle assessment

LNG – liquefied natural gas

GHG – Greenhouse gas

DoD – depth of discharge

CEU – Car equivalent unit

Pax - persons

1,4-DBC – 1,4- dichlorobenzene (toxic substance)

PM – Particulate matter

NMVOC – Non methane volatile organics

SO_x – Sulphur oxide

NO_x – Nitrogen oxide

CO_2 – Carbon dioxide

CH_4 - Methane

PDF – Potentially disappeared fraction

DALY - Disability adjusted life years

1 Introduction

Environmental performance of all-electric and conventional ferry concepts are evaluated in this thesis using the method life cycle assessment (LCA). Increased governmental focus on reducing emissions of greenhouse gasses (GHG's) in Norway are motivating increased use of all-electric ferries. Another incentive to find the most energy efficient and environmentally friendly ferry solution is the fact that the ferry fleet is aging and most likely will be renewed the coming years ("Innstilling til Stortinget fra energi- og miljøkomiteen," 2016).

In the following chapters a brief background, objective and scope as well as the limitations of this thesis is presented. A literature review on ferries is following before the ferry route Lavik-Oppedal is presented in depth. The methodology used is then presented before the model and inputs are described. The last chapters describes the results, discussion of them, conclusion and further work.

1.1 Background

On a global scale the marine transport sector is contributing to three percent of the total greenhouse gas emissions (IMO, 2014). Stricter policies are being deployed in order to reduce emissions from marine transport. These policies are intending to motivate sustainable technology development.

Norway's long coast with many fjords makes many of the main roads dependent on ferries transporting vehicles and persons across. The Norwegian government are deploying policies to reduce the emissions stemming from domestic transport. 745 000 tonnes of CO_2 were emitted from the ferry fleet in 2011. It can however be claimed that the ferries are a small proportion of Norway's total greenhouse gas emissions, and that the efforts are more costly than their effects (Nerheim, 2015).

The Norwegian government is focusing amongst other areas on domestic ferries in order to reduce greenhouse gas emissions in an innovative manner. Both the world's first liquefied natural gas (LNG) and battery driven ferry have been set into service in Norway.

LNG is a fuel with higher energy content than conventional fossil fuels per carbon molecule, meaning that the combustion of LNG emits less CO_2 per energy released. LNG does not contain sulphur, and the emissions of SO_x are eliminated. The engines does however have methane slip in a varying degree, contributing to emissions of GHG's.

Batteries are storing and providing electricity supplied from the electricity grid. They are resource and energy intensive to produce, but only have operational emissions from the electricity production. Advantages are also reduced vibration and noise. The disadvantages are the price of the batteries and the capacity limiting them to short routes with moderate speed. The ferries also need sufficient time at port in order to charge the batteries or change them if a mobile solution is used.

MS Ampere is the world's first battery car ferry in service and it operates on the ferry route between Lavik and Oppedal. The service is connecting the European highway E39 across the Sognefjord. Location of Lavik-Oppedal are shown in Figure 1 and Figure 2.

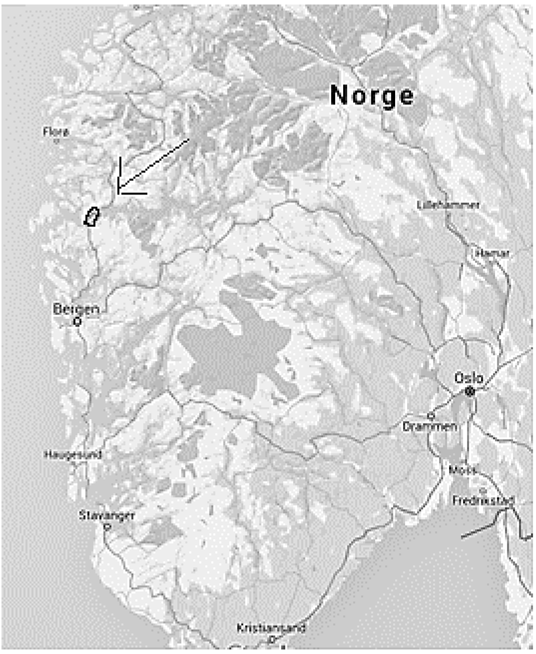


Figure 1: Location of the ferry route Lavik-Oppedal in Norway (Google Maps, 2015).

Figure 2: Regional map of the ferry route Lavik-Oppedal (Google Maps, 2015).

This ferry route was chosen as a basis for this thesis as direct data could be obtained on operating an all-electric ferry. The route is also close to the average ferry-route in Norwegian context (Statens Vegvesen, LMG Marin, CMR Prototech, & Norsk Energi, 2016). In this sense the specific results obtained in the study can be considered valid for Norwegian all-electric and conventional car ferries.

Life cycle assessment (LCA) is one of the most developed methods to evaluate environmental impacts associated with objects or systems providing services. The method is dependent on the researchers understanding and modelling of the item. Choices concerning what parts of the value chain to include, and which to omit can have large influence on the results.

1.2 Objective and Scope

This thesis is aiming to include the most relevant parts of a ferry in a LCA in order to compare environmental effects from different ferry concepts. A modern light-weight hull propelled by batteries and a conventional steel hull utilizing diesel electrical machinery are compared. In addition two theoretical cases where the same light-weight design as the battery ferry using liquefied natural gas (LNG) and diesel are considered. The comparison between the conventional ferry and the all-electrical one have been carried out in multiple studies, but they are including different parts of the systems and few are providing the data they have used. Comparing the same modern and light-weight ferry with different energy carriers isolates the difference in energy carrier. A transparent inventory should also be provided to assist future studies.

1.3 Limitations

A complete LCA is unfeasible as a master thesis, hence the most important parts of the value chain are included. This can give an incomplete set of results. Not all emission reducing measures and technologies are taken into account, and future studies should strive to include some of these. Examples are biofuels, scrubbers, fuel cells, etc.

Site-specific values are used where available while average values have been used where site-specific values have not been available. Data on commodities such as energy, metals and fuels were taken from a database using average values, since data collection of these values were considered too time consuming for this thesis. Some might argue that marginal values should be used, as the demand set by the ferry increases the total demand and hence the marginal production. The descriptions of what is included in these database values have not been available for all processes, and therefore incorrect processes may have been used.

2 Ferries

Ferries are and have been an important part of the Norwegian transport sector. In the following chapters the historic development of ferries as well as LCA studies conducted on ferries will be presented. The literature has been found by searching the Oria database provided by Norwegian University of Science and Technology (NTNU). The following key words have been used: environmentally friendly ferries, LCA, ferry, all-electrical ferry, batteries, LNG etc. Articles referenced by the ones found in Oria were then looked into.

2.1 Historic Development of Ferries

Ferries in various forms transports and has transported people and vehicles across waterbodies. The development of the railway in the late 1800's laid the foundation for the modern ferry to transport materials.

Before the 1930's no specialized car ferries operated in Norway (Arisholm & Kolltveit, 2007). The Norwegian authorities engaged in the matter after the Second World War. Ferries in this period were small and had a capacity up to 8 car equivalent units (CEU). Two characteristic car ferry designs have been developed, double ended and conventional hull. A double ended ferry has no defined bow and stern and therefore does not have to turn around when leaving port, the other end is turned into the bow. Double ended ferries were not common in Norway before the 1960's.

In Norway there has been a gradual increase in the ferry size since the 1930's. In the 1960's the first modern double ended ferries were produced. One wheelhouse became common in comparison to two separate ones on the double ended ferries. Conventional ferries were the majority of the fleet until the 1980's. The domination of the double ended ferries was closely related to size increase of the ferries due to increased traffic and demand for time savings. Size and design improvements made them a viable option in terms of seakeeping and resistance. A double ended ferry also saves time in terms of manoeuvring. Another trend is that some ferry routes with large amounts of traffic have been replaced by bridges or tunnels, where this has been feasible.

Another main driver in the design of ferries is safety regulations. A present ferry should not only be able to transport private cars but also trailers and trucks, some of them carrying dangerous goods. Many ferries built during the 1960-80's are still in operation they do not satisfy new regulations. Technical upgrades are in some cases possible, but it can be more expensive than the market value of the ferry (Arisholm & Kolltveit, 2007).

2.2 Current Ferries

As mentioned in chapter 2.1 most car ferries operating along the coast of Norway today are double ended. The typical ferry route is around 6,8 km according to Statens vegvesen (Statens Vegvesen et al., 2016).

The Norwegian ferry fleet is currently aging, and the government started incentives to renew the fleet in 1996, and the current focus is mitigating climate change impacts and increasing energy efficiency (Arisholm & Kolltveit, 2007). Some of the requests for tenders being developed have emission requirements that can only be fulfilled by newer ferries or specified technologies.

2.2.1 Environmental Measures in the Marine Sector

Several technological solutions to reduce environmental impacts and increase energy efficiency have evolved. The Norwegian government has set LNG fuelled and all-electric ferries as important technologies to reduce emissions of greenhouse gasses. Both the world's first LNG and battery powered car ferry were set into service in Norway in 2000 and 2015 respectively. LNG and batteries are described in the following chapters. Some parts of the chapter on batteries are copied from the researcher's project thesis completed during the autumn semester of 2015.

Liquefied Natural Gas

Liquefied natural gas (LNG) is a fuel with larger energy content per kg fuel, as well as lower carbon content than conventional fossil fuels. This means that less CO_2 is emitted per amount of energy from combustion. LNG is 85-95% methane (CH_4), and the rest is ethane, propane and butane (Statoil, 2014). It is odourless, colourless, non-corrosive and non-toxic. LNG has no sulphur content which eliminates the emissions of SO_x stemming from the fuel, and releases less particulate matter (PM). The use of LNG in marine transport is expected to increase as stricter emission regulations can be satisfied by using LNG. A disadvantage with LNG propulsion is the release of methane that has not been combusted. There are different types of gas engines;

- Lean Burn Otto cycle
- Dual fuel engines
- High pressure natural gas injection diesel cycle

The lean burn engine is often referred to as spark ignited, and operates with high excess air ratio. It has low emissions of NO_x and if the lambda control, or excess air regulation, is operated optimally the methane slip is low. Norwegian ferries operating on natural gas today are lean burn.

Dual fuel engines are similar to lean burn gas engines, but a diesel pilot flame is used to ignite the gas mixture instead of a spark plug. The amount of diesel increases at lower loads as well as the emissions of diesel-related stressors.

High pressure natural gas injection diesel cycle engines are working the same way as a diesel engine where the diesel is replaced by natural gas. This engine has larger NO_x emissions and has very low natural gas emissions. This engine type is used on some production ships where high pressure gas is available.

Batteries

Batteries only have indirect operational emissions stemming from electricity production. The production of batteries are energy and resource intensive. Li-ion batteries are being widely used for transport applications due to their low weight and volume compared to the energy they deliver. Current technology development on batteries are driving the prices and weight of batteries down.

A battery is made up of several small cells. A battery cell consists of an anode, cathode, separator and electrolyte. In Li-ion batteries the anode is made of lithium oxide, the cathode is carbon-based, the separator is a micro porous membrane and the electrolyte is lithium salts in organic solvents. When the battery is delivering electricity, electrons are being released at the cathode due to oxidation of lithium ions. This process is reversed when the battery is charged. A principal drawing of a li-ion battery cell is shown in Figure 3.

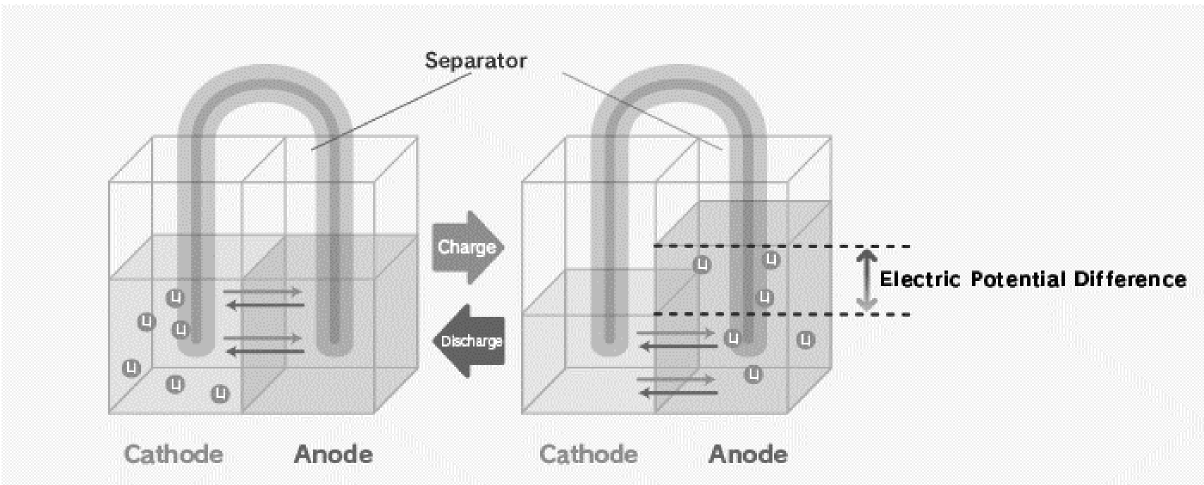


Figure 3: Principal figure of a battery (Automotive Energy Supply Corporation, 2013b).

A Li-ion cell has a voltage of approximately 3-4 V and several cells are coupled together in a module to obtain larger voltage (Automotive Energy Supply Corporation, 2013a; Corvus Energy, 2016a). The modules are coupled together to obtain larger voltage and capacity. A principal drawing of the build-up of a battery is presented in Figure 4.

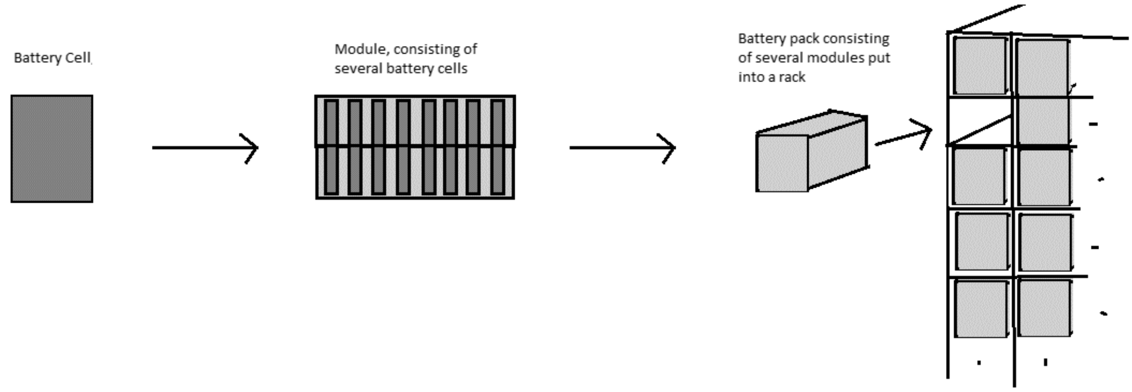


Figure 4: Battery package build up.

The lifetime of a battery is highly dependent on the usage and whether it is fully discharged or charged and a li-ion battery can survive 1,500-3,000 full discharge cycles (Patel, 2011).

Batteries used as energy storage for propulsion on board ships are considered feasible for vessels with short-distance routes that are not weather critical. Such vessels are certain ferries and fishing vessels. This is due to the size, weight and mostly cost a large battery would have in order to serve on merchant ships travelling longer distances.

Hybrid solutions combining electrical and diesel- or gas engines are also put into practice in order to reduce emissions on ferries, PSVs, tugs, super yachts and other specialised vessels (Corvus Energy). Hybrid solutions where the battery takes the peak loads in order to keep the internal combustion engine at optimal loads can reduce the emissions of conventional large ships substantially.

Batteries as marine power plants are evaluated as feasible and early in the development phase. Future emission reduction technology are expected to use batteries. For ferries specifically, a study conducted by the organisation Zero concluded that battery driven ferries would be a feasible option for many of Norway's ferry routes (Opdal, 2010). Adolfsson & Breivik set a limit to 200kWh per crossing for a ferry to be feasible for all-electric operation (Adolfsson & Breivik, 2014).

2.3 Life Cycle Assessments on Ferries

In recent years several LCA studies have been carried out on ferries. Studies with similar scopes as this thesis will be summarized in this chapter.

Schmidt & Watson looks at environmental savings on lightweight structures in carbon fibre (Schmidt & Watson, 2013). A ferry in carbon fibre is compared to a ferry with a steel based structure. The study concludes that large fuel savings can be achieved. Reducing the lightweight, the hull and equipment, with a factor of 3,5 gave a halving of the impacts in many categories. This was mostly due to a reduction in fuel consumption and the operation phase was pointed out to have the largest proportion of the environmental impacts. The two ferries compared are of different age, and this can be critically assessed. The eco-ferry in carbon fibre is on the conceptual stage and likely fitted with new technology, while the steel based structure is the ferry currently operating the route. This ferry was new in 1993 and it can therefore be argued that the results are somewhat optimistic, dependent on how the old ferry has been refitted with new technology as this affects the emissions, which has not been commented on in the report.

Mihaylov et al. carries out a comparative LCA on battery driven and diesel driven ferry, and the similar nature to the present study made it interesting (Mihaylov, Svensson, & Eklund, 2014). The ferry was being rebuilt to be battery driven, and operates in Stockholm. Only the propulsion train is included in the analysis, and there is no explicit comment on whether the rebuild alters the weight. This makes the results of the analysis somewhat vague as well as the unclear presentation of the results.

In January 2016 Statens Vegvesen presented a report on energy efficient and climate friendly ferry operations (Statens Vegvesen et al., 2016). It investigates hull shapes, energy storage and transformation systems, as well as combinations of the two reducing the environmental impacts associated with ferry operation. Emissions of CO_2-eq. are the only reported results. Cost and technological feasibility are also considered as well as the development of a digital tool to estimate tender criteria concerning environment and energy efficiency. Ferries with capacity of 20 to 290 CEU, with mono- or catamaran hull in either steel or aluminium were examined. The propulsion systems considered were:

- Diesel-mechanical
- Gas-electrical
- Diesel or gas electrical battery hybrid
- Battery
- Hydrogen

The concepts were evaluated varying the operational parameters:

- Number of ferries and size of them
- Hull type
- Speed and size
- Distance

According to the study battery driven ferries are the most environmentally friendly, but they have limitations. The limitations are high speed, long distances, time in port to charge and capacity limitations of the electricity grid. All-electric ferries also need several energy efficiency measures in order to reduce cost of the batteries. Hydrogen fuel cells are presented as a sustainable future option that needs to be tested on a large scale. Accessibility to the fuel also need evaluation.

Reduced speed and increased length of the ferry route and size increase the energy efficiency. This is in accordance to general “rules of thumb” in the maritime transport sector. Large ships have less emissions per tonne nautical mile (Balland, 2014). Operation in other modes than transit, such as manoeuvring, are often less environmentally friendly as engines are optimized for certain loads, hence increasing time in transit mode makes the ferry more environmentally friendly.

Several functional units have been used in the study by Statens Vegvesen:

- MJ/CEU-km
- gCO_2-equivalents/CEU-km
- gCO_2-equivalents/kWh

A functional unit reflects the purpose of the service being investigated and is explained in chapter 4. The two first functional units are reflecting the mission of the ferry to transport cars a distance. It is claimed that the functional unit of gCO_2-equivalents/kWh looks at the specific efficiency of the machinery and energy carrier. A ferry is however more complex than that, and a functional unit per kWh will also have dependencies to vessel resistance. This makes it difficult to distinguish what is evaluated, the ability to produce power efficiently or the design of the ferry. One ferry design can have large resistance, meaning that it needs a large amount of power and the power generation can be efficient, meaning a low emittance of CO_2 per kWh. Another ferry design with low resistance has less demand for power and the production is almost as efficient as the first design. Choosing the ferry option with the lowest emissions per kWh in this setting means picking the solution with largest environmental footprint.

Statens Vegvesen has made the study with empathies on operational measures. It does not include environmental impacts from production of “capital goods” such as ferries, engines and other infrastructure. This is justified by the claim that operation will be the most important contributor to the environmental impacts of the ferry. Batteries is not included and this simplification might underestimate the impacts associated with all-electric ferries due to battery replacement every 8-10 years.

3 The Ferry Route Lavik-Oppedal

The 5,6 km ferry route between Lavik and Oppedal are served by three ferries. Two of these, MS Ampere and MF Oppedal, are the foundation for this assignment. They have the same capacity:

- 120 car equivalent units (CEU)
- 350 passengers (pax)

The two ferry solutions differ in the type of energy carrier to provide power, hull form and hull material. MS Ampere use batteries to store and provide energy and is a catamaran built in aluminum. MF Oppedal is a monohull in steel using diesel as energy carrier and releases the energy through combustion. Figure 5 shows the difference between a catamaran, which has two smaller hulls, and monohull.

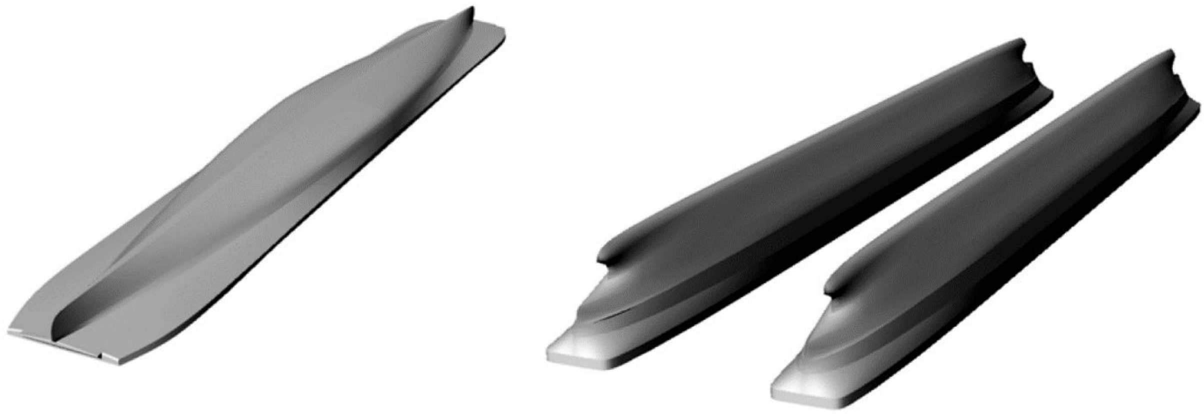


Figure 5: Monohull to the left and catamaran hull to the right (Statens Vegvesen et al., 2016).

As mentioned in the introduction, the analysis will include a comparison of MS Ampere and MF Oppedal as well as two theoretical versions if MS Ampere. The versions of MS Ampere are added to isolate the difference in energy carrier. Table 1 presents the different cases.

Table 1: Different ferry options divided on hull and energy carrier.

Case/ferry	MF Oppedal	MS Ampere	MS Ampere–gas (theoretical)	MS Ampere-diesel (theoretical)
Hull	Monohull	Catamaran	Catamaran	Catamaran
Energy carrier	Diesel	Batteries	LNG	Diesel

3.1 MS Ampere and MF Oppedal

On board MS Ampere several measures on energy- and weight savings have been deployed in order to reduce the size of the batteries. In order to save weight the hull is built in aluminium. It is also a catamaran and this configuration is providing favourable geometry and a large width, for the car-deck (Statens Vegvesen et al., 2016). MF Oppedal is made in the conventional hull material steel. It is a monohull, which in most cases has lower resistance than a catamaran (Statens Vegvesen et al., 2016). Figure 6 shows MS Ampere and MF Oppedal.

Figure 6: MS Ampere (left) and MF Oppedal (right) (Fiskerstrand, 2008; Froholt, 2015).

Key characteristics of the two ferries are presented in Table 2.

Table 2: Key characteristics of MS Ampere and MF Oppedal

	Capacity		LOA	LBP	B	D	V
MS Ampere	120 cars	350 passengers	79,4 m	78,6 m	20,8 m	6 m	9,5-10,5 kn
MF Oppedal	120 cars	350 passengers	114,0 m	104,9 m	16,8 m	5,5 m	11 kn

The ferries have several other systems and components where they differ, but the hull and energy providing systems are principally different. General systems and components are described in Table 3.

Table 3: Systems and comonents installed on MS Ampere and MF Oppedal

Ferry component	**MS Ampere (system components, and manufacturer) (Adolfsson & Breivik, 2014)**	**MF Oppedal**
Propulsion system	Azipull propellers, one fwd. one aft at one hull. Rolls-Royce	Azimuth thrusters, one fwd. and one aft. Schottel (STP 1010)
Hull	Catamaran in aluminium, with focus in low resistance. Built at Fjellstrand in 2015	Monohull in steel, built at Fiskerstrand in 2008
Power generation	Two electrical engines, one for each azipull, 450 kW Siemens AS	Diesel electric propulsion system from ABB (AMA450L6L BAFMH)
Energy providing	Two batteries with 500 kWh, Corvus Energy Electricity distribution system: BlueDrive PlusC, Siemens AS	2 x Mitsubishi (S12R-MPTA), 1110 kW 2xMitsubishi (S6R2-MPTK-F), 640 kW

The charging system at each port for MS Ampere is a pantograph and plug. The plug is lowered into the contact as shown in Figure 7 and Figure 8.

Figure 7: Charging station consisting of plug (left) and pantograph (right) (Siemens AG, 2015)

Figure 8: MS Ampere at port charging (Stensvold, 2015).

The electricity grid cannot provide sufficient power to charge the batteries during the time at port and therefore one extra battery is put at each port. The battery on board is charged by electricity from the grid as well as the extra battery. A principal drawing of the electricity transfer can be seen in Figure 9.

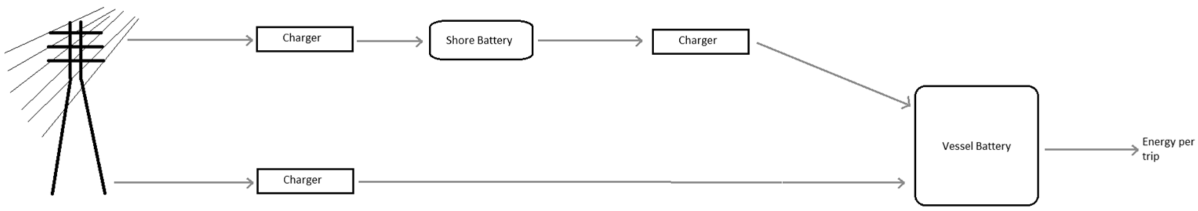


Figure 9: Principal set-up of electricity transfer from distribution grid to ferry.

MS Ampere is situated at port 10 minutes between each crossing and nine of them are used to charge the vessel batteries, it takes one minute to connect and disconnect.

MF Oppedal was originally built for another ferry route than it is currently operating, and the original design speed was larger than the one it is currently operating at. The installed power, which is matching a design speed of 13 kn, is therefore substantially larger than the current requirement. MF Oppedal is currently operating at a transit speed of 11 kn. Having larger engines than necessary can make the engines run on other speeds than optimal, giving larger fuel consumption and unfavourable emission characteristics. The present study therefore attempts to adjust the installed power to match the current operational profile of MF Oppedal. In that way, solutions designed for the same purpose, are compared. This procedure is described in chapter 5.3.5.

According to the crossing schedule MS Ampere has 32,9 crossings per day on a yearly average, accounted for holydays using 2015 as basis. The equivalent number for Oppedal is 43,9. When contacting the chief technology officer at Norled, the ferry operator, Sigvald Breivik, the researcher found out that the schedule is based on the minimum demand of the tender. A third of the crossings should be carried out by the all-electric ferry. Sometimes the ferry operates more than listed, but it has pauses of 30 minutes every once in a while in the time table to counteract possible failed charging. The timetable values have been used in the present study.

In order to simplify the analysis downtime and energy consumption during night are omitted and it is assumed that maintenance can be carried out during night. Emissions when bunkering fossil fuels are not included due to lack of data and indications on the fact that these emissions are a small part of the total emissions from the fuel value chain (Ryste, Utne, & Martin Wold, 2012).

4 Life Cycle Assessment

This chapter is with the exception of chapter 4.5 is partly copied from the researchers project thesis completed 18.12.2015. Increased globalisation makes the evaluation of environmental impacts complex. This is mainly due to the trading patterns in both production and end of life, involving numerous locations and companies. Emissions occurring indirectly are also desirable to include as they are emerging from the task they are supporting. LCA is a method with emphasis on including all impacts in order to identify potential problem shifting. Problem shifting means to decrease impacts on expense of increasing impacts either in other places in the value chain or other types of impacts.

Life cycle assessment is a method assessing environmental impact from products and product systems where emphasis has been put on consistency when comparing different technologies (Strømman, 2010). The international standard ISO 14040 serves as a framework for LCA studies, and the general categories considered are resource use, human health and ecological consequences(Klöpffer & Grahl, 2014). LCA as a method is relatively new and the first analysis in modern sense were carried out around 1970. The idea of life cycle thinking is however old and the first report on such thinking was presented by the Scottish economist and biologist Patrick Geddes in the 1880s. LCA can be divided in four parts;

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

The three first phases are carried out in the order they are mentioned, while interpretation is important during all steps. Figure 10 shows the different phases as well as their connections.

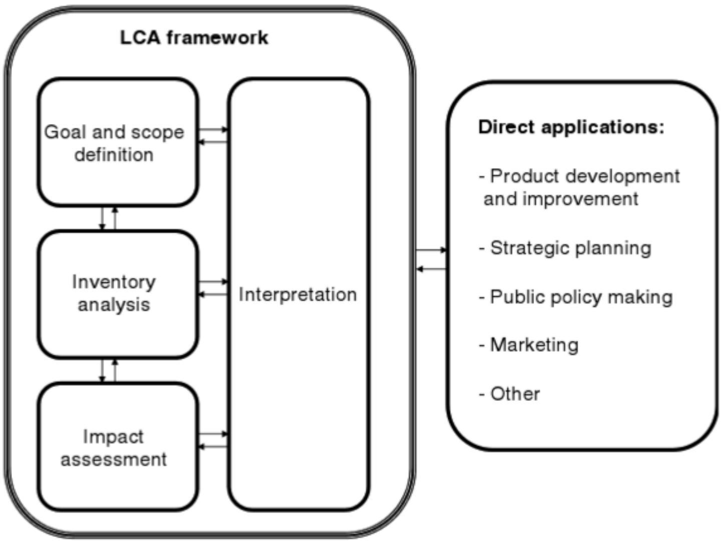


Figure 10: LCA framework (ISO, 2006)

The next chapters present the theory behind LCA as well as the line of action in the method.

4.1 Goal and Scope

The first step in a LCA is the definition of the goal and scope of the study. The goal consists of the motivation to execute a LCA. It can be environmental law and policy, comparison of products, communication of impacts, waste management and enterprise (Klöpffer & Grahl, 2014). Who the LCA is made for and the accessibility of the study and data used has to be decided.

The scope consists of clearly describing the product or product system(s) in order to look at the systems function. A flowchart can be used to visualize the system. Both direct and indirect activities are included, and the aim is to define total environmental impact from one functional unit. The functional unit is the product or service that is analysed. An example can be the emissions associated with producing one kWh of electricity or 1 MJ heat.

When the functional unit is defined, the system boundaries are defined. System boundaries should include all significant parts of the functional unit's lifecycle regarding materials, infrastructure and other inputs. By definition all parts of a system should be included. Parts omitted should be known to have little impact (Klöpffer & Grahl, 2014). On the other hand a system including all indirect systems and processes can become infinitely large. Therefore reasonable boundaries has to be set in order to get a system within practical limits. A cut-off criterion regulates the exclusion of insignificant inputs to the system. The criterion can be based on mass, energy or environmental relevance (ISO, 2006). A proportion such as 1% of mass, energy, etc. is often set as a cut-off criterion (Klöpffer & Grahl, 2014). The environmental relevance should be looked at when dealing with substances having large impacts even in small masses. In order to know what data to collect, the methods to quantify impacts described in chapter 0, also have to be defined at the start of the analysis.

4.2 Life Cycle Inventory

Life cycle inventory (LCI) concerns the collection and structuring of data to be used in the analysis. Baumann & Tillman divides this phase in three parts; construction of flowcharts according to system boundaries, data collection and documentation as well as calculation of the environmental loads (Baumann & Tillman, 2004).

4.2.1 Open Leontief Model

There are many approaches to describe the mathematics behind LCI, and here a linear dependency between the processes are assumed. Figure 11 shows a schematic of a production system, where the a_{ij} coefficients are the relationship between input from i and output from j, external demand is described as y_{ij}. The letters i and j represent numbers written on general form for the rest of this chapter. It is desirable to establish a flowchart similar to the one in Figure 11 in order to carry out the calculations following.

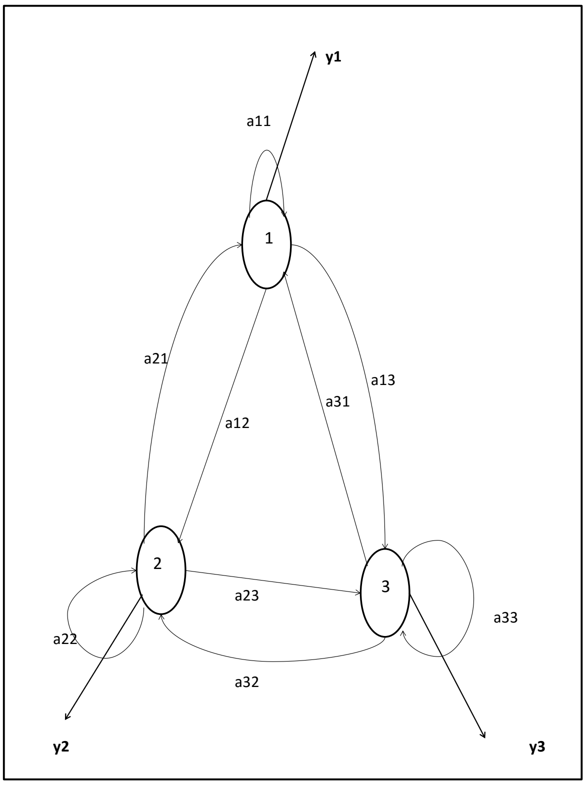


Figure 11: General flowchart for the production balance, where a_{ij} is the amount of throughput of process i required per unit produced from process j. y_i represents the external demand from process i

In order to explain simpler Figure 11 will be used as a basis when defining and explaining further variables. The vector of requirement for each process can be established as in (1).

$$a_{i2} = \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \end{bmatrix} \tag{1}$$

a_{22} is the inputs from the process itself per output from it. In many cases this is equal to zero, although for some cases it will be unequal to zero, and is therefore included when setting up a general framework. All vectors of requirement can be set in a matrix, the requirement matrix, as in (2).

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{a_{11}} & \boldsymbol{a_{12}} & \boldsymbol{a_{13}} \\ \boldsymbol{a_{21}} & \boldsymbol{a_{22}} & \boldsymbol{a_{23}} \\ \boldsymbol{a_{31}} & \boldsymbol{a_{32}} & \boldsymbol{a_{33}} \end{bmatrix} \tag{2}$$

This matrix will be used to calculate the flows based on the external demand. In order to set up a production balance the x-vector that refers to the production output per node to cover the demand y_j has to be calculated. For node 2 the throughput, x, can be determined using (3).

$$x_2 = a_{12} * x_1 + a_{22} * x_2 + a_{32} * x_3 + y_2 \tag{3}$$

x_2 represents the total output required at process 2 in order to cover the external demand. For all processes (3) can be generalised into a matrix equation as shown in (4).

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \tag{4}$$

In matrix form this can be written as in (5).

$$\boldsymbol{x} = A\boldsymbol{x} + \boldsymbol{y} \tag{5}$$

(5) is then solved for the unknown output from the processes, the x-vector, through the following steps;

$$(I - A)\boldsymbol{x} = \boldsymbol{y}$$

$$\boldsymbol{x} = (I - A)^{-1}\boldsymbol{y}$$

It is normal to set;

$$L = (I - A)^{-1}$$

where L is the Leontief Inverse. It represents the output, x, of process i that is required per unit of final delivery or external demand, y, of process j. Another vital assumption is that all processes are self-sustaining, implying a positive determinant of (I-A).

4.2.2 Life Cycle Phases

In order to include different life cycle phases in a unidirectional model, (6) can be used to include contributions of for example construction and demolition of a facility used in the making of the functional unit in operation.

$$a_{CiOi} = \frac{1\, functional\ unit}{total\ production\ over\ lifetime} = \frac{1}{\dot{m} * \tau_{life}} \tag{6}$$

4.2.3 Contribution Analysis

In chapter 4.2.1 the output per process due to external demand was set. The life cycle impact assessment relates the amount of product to environmental stressors. Stressor is a term concerning emissions and other environmental impacts such as land use quantified in an impact assessment. Several matrixes' will be defined, and the first one is the stressor matrix, S. It describes the stressor, environmental load, associated with one unit of output from each process. The definition of the stressor matrix is given in (7).

$$S = \begin{bmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{1,str} & \cdots & s_{str,pro} \end{bmatrix} \tag{7}$$

Processes are put in separate columns; the stressors are set as one stressor per row of the matrix. The value in s_{11} represents the amount of stressor 1 due to one output of process 1. Stressors ca be a substances such as CO_2, NO_x, or other properties that can be quantified.

A desired result of an LCA is the cumulative impacts the functional unit has. It can be found by multiplying the stressor matrix with the output per process, the x-vector, as shown in (8).

$$e = \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = Sx \tag{8}$$

The e-vector expresses the total amount of each stressor generated due to one functional unit. Another desired result providing more detailed insight is a quantification of what processes the different stressors come from and this calculation is presented in (10). The same method as (8) can be utilized, but the x- vector is altered. It is transformed into a diagonal matrix, meaning that the values in the x-vector are set on the diagonal of a matrix that otherwise contains zeros as shown in (9).

$$\hat{x} = \begin{bmatrix} x_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & x_{pro} \end{bmatrix} \tag{9}$$

$$E = S\,\hat{x} \tag{10}$$

The columns in the E-matrix represent the different processes, and the different stressors are represented in each row. This matrix is useful in order to determine the processes contributing the most to generation of the different stressors, hence where the largest improvement potential is. Another feature of the E-matrix is if all values in each row are added the total stressors are found, as presented in (11).

$$e = \sum\nolimits_{pro} E_{str,pro} \tag{11}$$

4.3 Life Cycle Impact Assessment

In order to relate the results to environmental issues, a characterisation matrix is used. The numbers in this matrix convert the amount of stressor to an equivalent stressor in a particular impact category. Impact categories are the different environmental issues and some examples are; global warming, human toxicity, water depletion and fossil resource depletion. Global warming is measured in CO_2 equivalents, as CO_2 is the equivalent stressor. Human toxicity is measured in 1,4-dichlorobenzene(1,4-DBC) equivalents. The characterisation matrix' rows represent the different impact categories and the columns denote the different stressors as shown in (12).

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp} & \cdots & c_{imp,str} \end{bmatrix} \tag{12}$$

Total impacts from one functional unit can be found when multiplying the characterisation matrix with the vector of total stressors. This is presented in (13).

$$d = Ce \tag{13}$$

In order to distinguish the amount of impact on the different processes the characterisation matrix are multiplied with the matrix that divides the different stressors on the different processes, calculated in (10), as shown in (14).

$$D_{pro} = CE \tag{14}$$

The D_{pro} matrix has one column per process and the impact categories in the rows. Stressors dominating the different impact categories are another interesting result. It can be found by multiplying the characterisation matrix with the diagonal form of the total stressor vector e as shown in (15).

$$D_{str} = C\hat{e} \tag{15}$$

D_{str} has the different processes as columns and the stressors as rows.

4.3.1 Foreground and Background Systems

It is normal to divide between the system being investigated in depth and the processes that are needed to complete the upstream value chain as foreground and background. Data collected for the study are often in the foreground and background data are often taken from generic databases.

The A matrix can divided in four parts, inputs from background to background and foreground as well as inputs from foreground to foreground and background. This is assembled as presented in (16).

$$A_{ij} = \begin{bmatrix} A_{ff} & A_{fb} \\ A_{bf} & A_{bb} \end{bmatrix} \tag{16}$$

The A_{fb} is normally equal to zero as the system is considered unidirectional, which most production systems are. It is interpreted from that the background does not get any inputs from the foreground. In order to perform more advanced contribution analysis the stressor matrix is defined in foreground and background systems as in (17).

$$S_j = [S_f \quad S_b] \tag{17}$$

This enables a division on background and foreground when assessing impacts. The output specific to the foreground system can be calculated as shown in (18).

$$x_f = \left(I - A_{ff}\right)^{-1} y_f \tag{18}$$

x_f gives the output of the foreground system due to demand from the foreground processes. Now the demand from the background due to the foreground systems can be found as given in (19).

$$M_{bf} = A_{bf}\widehat{x_f} \tag{19}$$

The output from the different background processes output due to the foreground processes can be calculated using (20).

$$X_{bf} = (I - A_{bb})^{-1} M_{bf} \tag{20}$$

Impacts can be calculated in a similar manner, and the impacts from the different foreground processes are given in (21).

$$D_{pro,ff} = CS_f\widehat{x_f} \tag{21}$$

The impacts occurring in the background system occurring due to each of the foreground processes are calculated using (22).

$$D_{pro,bf} = CS_bX_{bf} \tag{22}$$

This enables the possibility to look at impacts associated with the different foreground processes and the total impact of the foreground processes, with background processes included are given in (23).

$$D_{pro,f} = D_{pro,ff} + D_{pro,bf} \tag{23}$$

$D_{pro,f}$ can be used to identify which processes have the largest total impact.

4.3.2 Midpoint and Endpoint

The impacts presented in chapter 4.2.3 are called mid-point indicators. This is the number of CO_2 equivalents etc. generated by the functional unit. Another impact category is the endpoint level indicator. It relates the impacts to direct effects on human health, ecosystem quality and resource scarcity. Impacts on human health is measured in disability adjusted life years (DALY), ecosystem quality are measured in potentially disappeared fraction (PDF) or species year. Resources are measured in the cost increase in $. The transformation from inventory to midpoint and endpoint is presented in figure 12 for the ReCiPe conversion method.

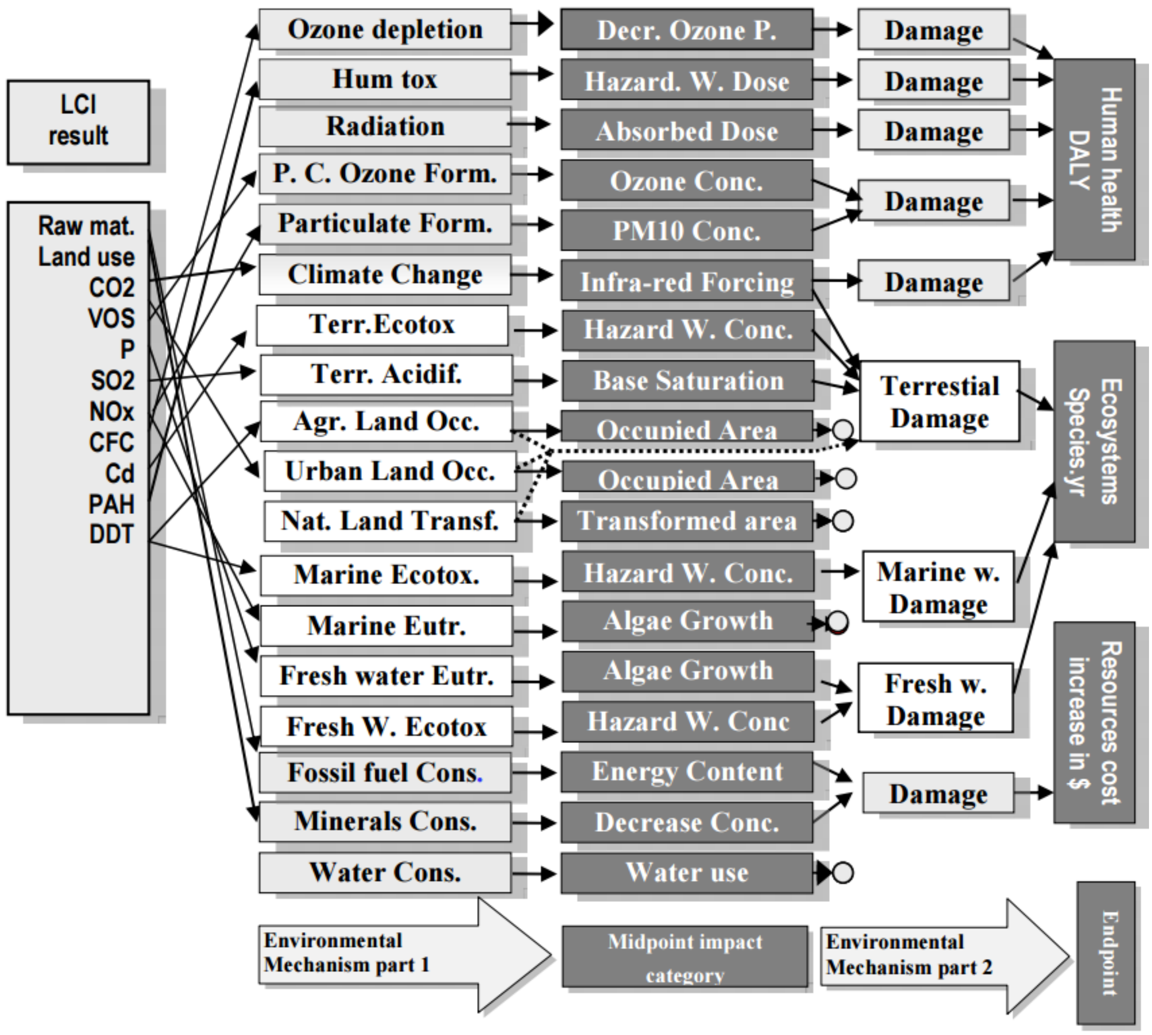


Figure 12: Conversion from stressors to mid- and endpoint characterization (Goedkoop et al., 2009).

There are several standards relating stressors to midpoint and endpoints, and the most common one is ReCiPe. Some impacts are stopping at the midpoint level and these are water use, transformed area and occupied area. Conversions of stressors to impacts are dependent on characterisation factors. These are reliant on on what perspective the impacts are viewed from. Three views are used; egalitarian, hierarchist and individualist. The egalitarian represents a long term, careful and argument-based view. Individualists are looking at short-term and require indisputable cause effect relations in order to take actions. Hierarchists are somewhat in between, being risk neutral and looking at intermediate time horizon. The different perspectives views on different topics are presented in Table 4.

Table 4: Egalitarian, Hierarchist and individualist views (Verones, 2014)

	Egalitarian	Individualist	Hierarchist
Criteria	Arguments	Experience	Evidence
Management style	Precautious	Accomodating	Controlling
Attitude towards environment	Respectful	Non-interfering	Regulating
Attitude towards risks	Risk adverse	Willing to take risks	Neutral
Time perception	Long-term	Short-term	Balanced
Perception of humans	«shapeable»	Egoistic	Erring
Perception of Nature	Transient	Good-natured	Capricious, tolerant

For global warming the different perspectives have different time horizon as different greenhouse gasses have different lifetime in the atmosphere as shown in Figure 13. Egalitarian, hierarchist and individualist have time-horizons of 500, 100 and 20 years respectively (Goedkoop et al., 2009).

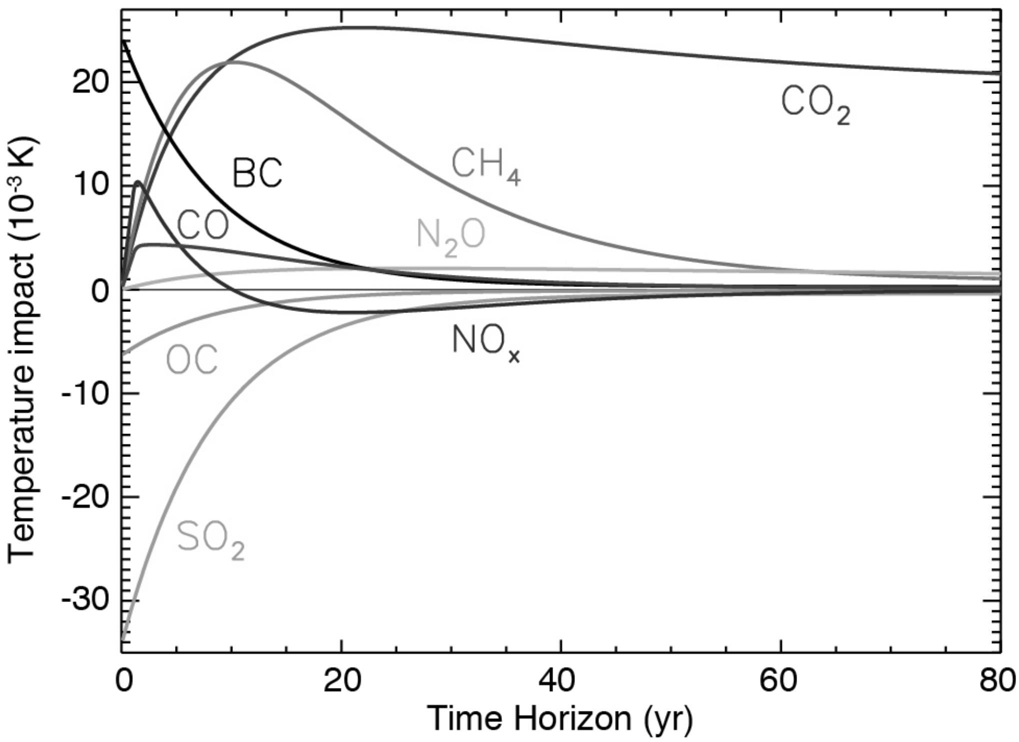


Figure 13: Temperature impact over time horizon (IPCC, 2013)

The relations between impacts and midpoints as well as endpoints are dependent on characterisation factors that are not entirely consistent, and therefore this type of classification of the results should be used with caution. Some argue the midpoints are most applicable due to less uncertainty in the results, as most have sufficient research behind the parameters (Bare, Hofstetter, Pennington, & Haes, 2000). The endpoint characterisations on the other hand are subject to more parameters, and the cause-effect relations are not always well documented. Endpoint characterisations are on the other hand useful if decision makers want less numbers to look at as well as more relatable numbers (Bare et al., 2000). Global warming potential is mostly affecting human health through an expected increase of malaria, and other similar connections might not be understood properly by the ones conducting and using the studies (Bare et al., 2000).

Midpoint categories used in the ReCiPe categorisation method and their environmental setting will be presented briefly in the next chapters. Endpoint characterisation will not be carried out in this thesis. Impacts not accounted for in LCA are noise and ReCiPe excludes odour. The results can be misleading if impact categories displayed as results are chosen with a bias, as a lot of processes have small impacts in some categories and larger in other.

Land Use

In ReCiPe land use can be divided between land occupation and natural land transformation. Occupation is divided between agricultural land use and urban land use and is quantified in m^2. Land use is not an environmental impact, but represent aspects of concern. Mining or landfilling are activities which might occupy different types of land (Goedkoop et al., 2009). Natural land transformation represents the transformation of land from for example rain forest or sea and ocean into commercial areas. The midpoint unit is m^2.

Global Warming Potential

Global warming potential or climate change impacts express the impacts converted to CO_2 equivalents and it therefore describes the amount of added greenhouse gases to the atmosphere. Greenhouse gasses reflect some of the longwave radiation from the earth back to the atmosphere giving net warming of the globe. Anthropogenic activities are increasing the amount of greenhouse gasses in the atmosphere and this gives a net increase in global temperatures (Alexander et al., 2013). Different gases also have different lifetimes in the atmosphere, as mentioned in chapter 4.3.2.

Resource Depletion

There are different types of resources that can be depleted, and ReCiPe quantifies three: metals, fossil fuels and water.

Mineral resources are considered as finite economically, and this impact category expresses the extracted mineral in kg iron equivalents. For metals the ore grade is decreasing with increased extraction and this increase will yield larger energy inputs to extract the same amount of mineral in the future, and also increase the cost, which is the endpoint unit for resources (Goedkoop et al., 2009). Impacts associated with mining activities are not included in this impact category as it only assesses the availability of the minerals.

Resources containing hydrocarbons such as methane, liquid petrol and coal are looked at in fossil fuels. The concept is similar to the one of mineral depletion, but for these resources the ore grade is not declining in the same way as the minerals. The midpoint characterisation factor is given in kg oil equivalents.

Water is a resource that is scarce in some parts of the world and abundant in others, and there is no global supply distributes water as the transport costs are high (Goedkoop et al., 2009). Water can be used in different ways, it can either be consumed close to the point of extraction before it is released and the consumption does not result in water shortage. In other cases the water can be transported and released at another location contributing to water shortage. There are also water consumption between the two mentioned levels, for example runoff systems in cities removing water from surfaces and hence removing the possibility to increase the groundwater level. The midpoint level measures water depletion in m^3.

Toxicity

Toxicity reflects the relative amount of toxic substance related to 1,4- dichlorobenzene (1,4-DCB) equivalents. Substances can have different toxicity to humans, terrestrial, freshwater and marine systems. Important factors to consider in relation to toxicity are fate, exposure as well as intake and effect (Baumann & Tillman, 2004).

Eutrophication

Nutrients are the limiting factor of aquatic life and when excess nutrients are released in water eutrophication can occur. This can cause algae blooms and depletion of the oxygen in the water which can lead to death of aquatic animals. Nutrients are mostly in the form of nitrates and phosphates and the main sources in terms of emissions are fertilizer, detergents and sewage. Both freshwater and marine waterbodies can be affected by eutrophication. It is measured in kg phosphor equivalents at the midpoint for freshwater, and kg nitrogen equivalents for marine waters.

Ionising Radiation

Ionising radiation are radiation from radioactive material having enough energy to remove electrons from an atom creation an ion. This makes the atoms charged and the chemical behaviour is changed. The overall conclusion is ionising radiation increasing the chances of developing cancer. The midpoint unit is given in kg Uranium 235 equivalents.

Ozone Layer Depletion

The ozone layer hinders most UV-B radiation from reaching the earth surface (Goedkoop et al., 2009). In the stratosphere ozone is continuously created and destroyed. Some substances released from human activities are reaching the stratosphere where it reacts with ozone, decreasing the amount of ozone in the stratosphere. Substances having these effects are converted into chlorofluorocarbon (CFC) equivalents.

Particulate Matter Formation

Particulate matters (PM) are a mixture of extremely small particles and liquid droplets coming from acid, organic chemical, metal, soil or dust components (United States Environmental Protection Agency, 2016). Smaller particles pose larger health risk to humans. Particles smaller than 10 micrometres in diameter are a special concern as they pass through the throat and nose and enter the lungs where they further can affect heart and lungs. At the midpoint level particulate matter is measured in PM_{10}equivalents meaning particles smaller than 10 micrometres.

Photochemical Oxidation

Photochemical oxidation is reactions that take place between nitrogen oxides and hydrocarbons create photo-oxidants in the lower atmosphere (Baumann & Tillman, 2004). These substances are most commonly known as smog, and it causes irritation to the human respiratory system and also damage vegetation. Ozone is the most common photo-oxidant, and it is important to divide between ozone in the lower atmosphere and the ozone layer in the stratosphere. The midpoint unit is given in kg Non-Methane Volatile Organic Compounds (NMVOC).

Acidification

The ReCiPe definition of acidification is defined as *"Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates, cause a change in acidity in the soil".* ReCiPe therefore only looks at the effects of acids on terrestrial ecosystems. Most organisms have a range of PH in the soil they can live under, and if the acidity exceeds this range it will have large effects on the species. Acidification is measured in kg SO_2equivalents and important substances contributing ot acidification are SO_2 and NO_x.

4.4 Interpretation

Interpretation is important in all steps described above. It is a final evaluation of the results and should contain identification of the most important numbers, their consistency and sensitivity. The conclusions and recommendations drawn should be stated as well as a critical review of them (Klöpffer & Grahl, 2014). It is important to evaluate the data quality and if the applied methods are sufficient for the results presented.

4.5 Recycling in LCA

A generic recycling process consists of the primary resource being extracted, put into a product and used before it becomes obsolete and is recycled. Recycled material is then used for a new product. The number of loops a material can undertake is dependent on the material type and impurities. Figure 14 shows a generic recycling loop.

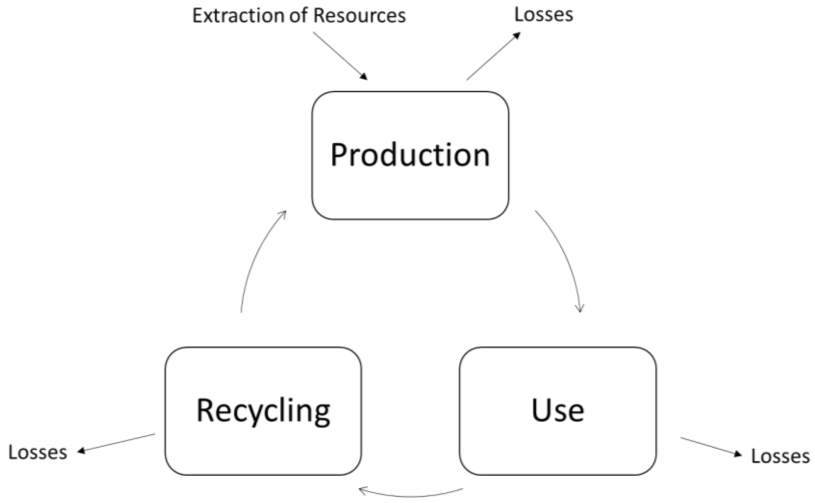


Figure 14: A Generic recycling loop.

In an LCA one is interested in the stressors associated with the round of the loop that concerns the item under investigation. It is common practice to either use secondary, recycled material as input or to deduce some of the impact associated with resource extraction. This avoids the problem of determining the number of loops a material can undertake.

5 Life Cycle Assessment Model

The following chapters presents the software used, the goal and scope of the analysis as well as data collection and structuring.

5.1 Arda Gui 1.8.1

The software used to perform the life cycle assessment calculations were Arda Gui, version 1.8.1, an educational LCA software developed at the Industrial Ecology Programme under Department of Energy and Process Engineering at NTNU. It requires an input template in Microsoft Excel and uses the Ecoinvent 2.2 database for generic processes specified in the excel template. The midpoint characterization method used in this assignment is ReCiPe version 1.08. Arda Gui is run in MATLAB R2014, and the results can be written out in excel for further processing.

5.2 Goal and Scope

5.2.1 Functional Unit

The function of a car ferry is transporting people and vehicles across waterbodies. A functional unit should somehow reflect this function in the best possible way. In the literature the functional unit of tonne nautical mile are used to reflect the freight work merchant ships carry out. Schmidt & Watson use the functional unit of operating a ferry service for one year when comparing two ferries (Schmidt & Watson, 2013).

Other options are the amount of load per trip, where either the average ferry load or the capacity of the ferry is used. The latter were used by Statens vegvesen et al. in their report, justified by the argument the ferry capacity is well dimensioned (Statens Vegvesen et al., 2016). A functional unit of amount of stressor per car equivalent unit transported one kilometer (CEU-km) were used.

Statistical data form Statens vegvesen were used to find the year average of normal sized cars and persons per day transported between Lavik and Oppedal (Statens Vegvesen & Vegdirektoratet, 2012). The ferry route table of 2015 were used to estimate the average number of crossings per day (Norled, 2015). An average value of 28 CEU and 17 persons (pax.) per crossing were calculated, the values used and calculated are presented in Table 5.

Table 5: Numbers used and calculation of average ferry load Lavik-Oppedal

	Average values
CEU / 24 h	2770
Pax. / 24 h	1695
Number of crossings / 24 h by the three ferries operating the route	98
CEU / crossing	**28**
Pax. / crossing	**17**

A larger number of cars than the number of passengers seems illogical at first sight, but can be explained by the fact that the ferry transports different kinds of traffic. The different road transport modes correspond to different CEU. A bus is for example equivalent to four CEU, and other typical vehicle to CEU conversions according to Statens Vegvesen is presented in Table 6 (Statens Vegvesen & Vegdirektoratet, 2012).

Table 6: Conversion for different types of road vehicles (Statens Vegvesen & Vegdirektoratet, 2012).

Type of car	**Number of CEU**
Personal car	1
Personal car with trailer	3
Van	1
Truck	3
Truck with trailer	5
Bus	4
Motorcycle	0

28 CEU and 17 pax compared to the capacity of 120 CEU and 350 pax reflectes a low utilization of the ferries. An evaluation of the utilization of the ferries are considered outside the scope of this analysis. A functional unit of per year operation or per capacity CEU-km is reflecting the same result but in different representations. The per capacity CEU-km unit could make the results easily comparable to other modes of transport, although it should be stated clearly whether the theoretical capacity or actual utilized capacity is used. A functional unit of per trip basis were used, although the results can easily be converted to per CEU-km or per year basis.

5.2.2 System Definition and Cut-Off Criteria

Comparing different ferries is a complex task and the following attributes should be taken into account;

- Speed
- Distance
- Capacity
- Infrastructure

MF Oppedal and MS Ampere travel at different speeds, and have slightly different infrastructure regarding fuel/charging systems. This could imply that MS Ampere needed more time at port to charge the batteries, but because MF Oppedal is using more time to manoeuvre and accelerate the times at port are modelled as equal. MS Ampere has fewer crossings per day as the timetable has gaps in cases of missed charging. Fewer crossings per day gives lower utilization of the ferry, and should be taken into account in the analysis.

When modelling the different versions of MS Ampere all attributes were assumed equal in order to simplify and to isolate the difference regarding energy carrier.

The optimal solution would be to include all aspects of production, operation and end of life for the ferries. Access or research on all this data is however not feasible. It was therefore looked into what parts of the life that would have largest impact on the analysis. As described in chapter 2.3 the operational phase is pointed out as the most important part of the life of ferries. It is expected a similar trend as with all-electric cars on the all-electric ferry, being that the production is increasingly important as the operational emissions are reduced for some impact categories (Hawkins, Singh, Majeau-Bettez, & Stromman, 2013). The difference in hull material between MS Ampere and MF Oppedal and the fact that the hull is a large proportion of the production costs motivates the inclusion of production of the hull. Other aspects that are attempted to include in the analysis are items that are principally different for the two ferries, for example the batteries and the engines. No specific cut-off criteria was established as one of the limiting factors of this study is information availability.

5.3 Life Cycle Inventory

Flowcharts according to system boundaries were made in order to start collection of data.

These are presented in Figure 15 and Figure 16, and include the largest inputs to the three operational phases of the ferries: production, operation and end of life. Upstream processes for production is the hull and for the all-electric ferry batteries, while the conventional ferry has hull and engine. The processes furthest to the left are considered background processes, which consist of material, energy and transport inputs.

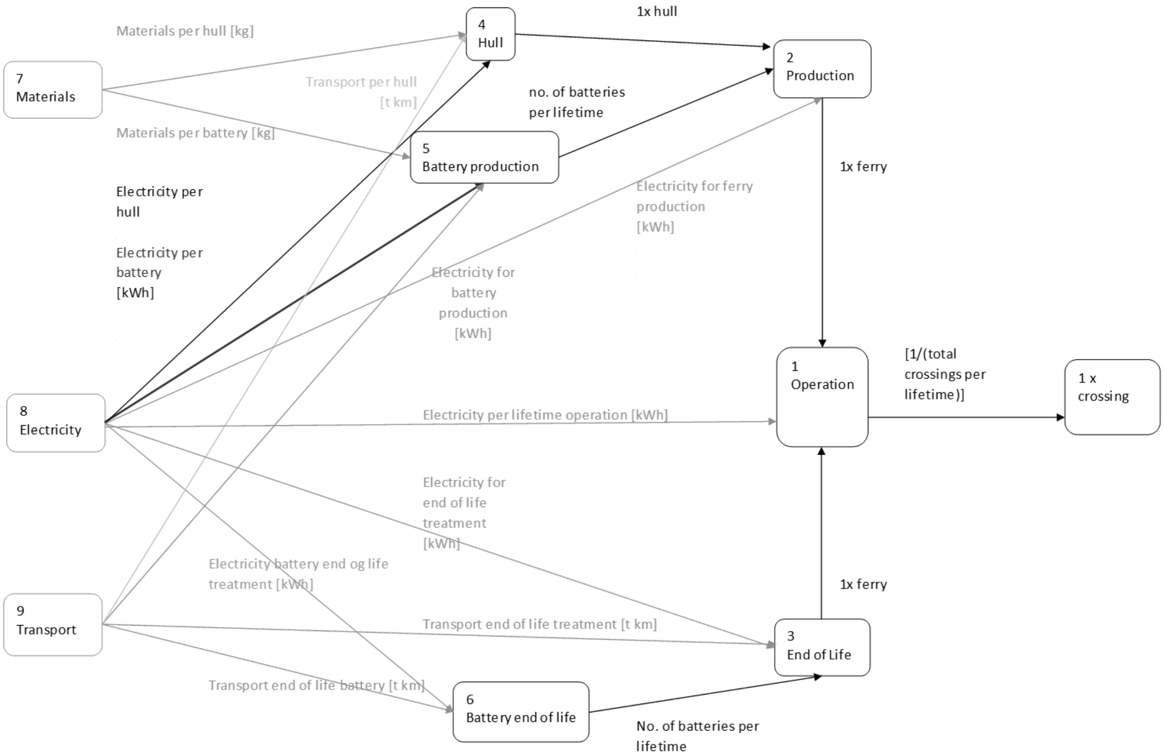


Figure 15: Flowchart all-electric ferry.

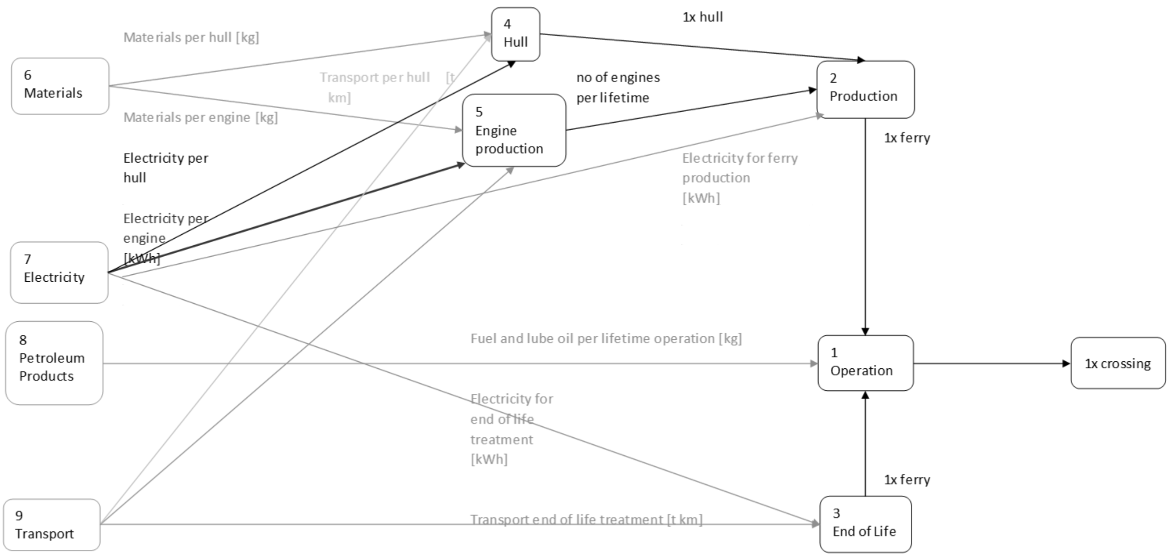


Figure 16: Flowchart conventional ferry.

The data was collected by reading articles as well as contacting different companies within the ferry industry. As some of the data were considered business secrets the researcher estimated these using theoretical knowledge according to engineering principles. In the following chapters the collection and structuring or calculation of the input data to the analysis is described. Full inventory, the input file to Arda Gui, is available in Appendix A – Input File Arda Gui.

5.3.1 Hull Production

Only raw materials in terms of steel and aluminium are included in the ferry production. An estimation of energy consumption and transport inputs proved to be unmanageable as the shipyards are individual and most do not have this information available. Several shipyards were contacted by the researcher and the main issues were availability of that data, individual processes and layout of different shipyards. An increasingly global value chain also divides different parts of the hull production between different shipyards.

Edmund Tolo, the sales manager at Fjellstrand shipyard, estimated 400-420 tonne aluminium as input to the production of MS Ampere. For MF Oppedal the estimate were around 1,000 tonne steel as input to the hull production. 420 tonne aluminium and 1,000 tonne steel were therefore used in the analysis.

5.3.2 Battery Production

The batteries are assumed to be a substantial part of the impacts associated with the electrical ferry. The electrical ferry has battery capacity of 1040 kWh installed on board and 420 kWh at each port.

Inventory data concerning the batteries were estimated based on data from a car battery pack. The study "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack" were used (Ellingsen et al., 2014). The marine and the car battery in the study, has the same cell chemistry, lithium-ion nickel-cobalt-manganese. Usage of the data was therefore considered an accurate estimate of the environmental costs of producing a battery, and collection of inventory was avoided. The battery cells, modules and packs are however different in size, voltage and capacity. Adjustments made in the battery dataset were carried out with assistance from PhD candidate Linda A. Ellingsen. Figure 17 illustrates the differences between the two batteries.

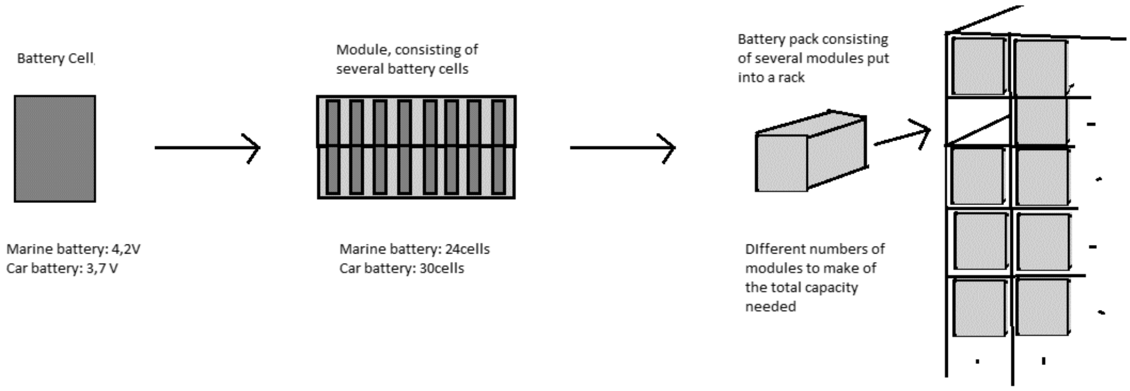


Figure 17: Principal differences between car and ferry battery pack.

Modifications were made in relation to energy consumption for cell assembly, sustaining racks, module packaging and the battery management system (BMS). The marine batteries inventory were estimated for the two packs of 520 kWh on board Ampere, and the two 410 kWh shore batteries. A total of 1860 kWh were therefore required for the process called battery production. It was assumed that all batteries would have the same lifetime, even though they are used differently. The shore batteries are used half the number of cycles as the vessel batteries, but they are utilized at higher DoD. Ten years lifetime for both batteries were therefore considered a sufficient estimate as the literature ranges between 8-10 years (Patel, 2011).

Battery cells were scaled to match the total capacity in terms of kWh. The cell ingredients in the marine battery were assumed to be relatable to internal proportions of materials in the car battery per kWh. The energy consumption during cell assembly was reduced by 50% due to rapid developments within the field as well as economies of scale, recommended by Linda A. Ellingsen (Ellingsen, 2016).

The racks assembling the battery modules into the battery packs were assumed to be principally different from a car battery. The weight of the racks were estimated based on the outer measures of the modules and description of the marine battery packs on the manufacturer's webpage (Corvus Energy, 2016a). Racks were assumed to cover the entire module except one end of the box where the battery management system was situated. Figure 18 shows a module and then modules set into racks making a battery pack.

Figure 18: Marine battery module (left) and modules set into racks (right).

The racks were made of steel and had an assumed thickness of 1 mm, and surrounded the modules with the outer measure of 59x33x38 cm. This were multiplied with the actual number of modules in the marine batteries, not the number of modules in the battery the inventory were scaled from. In relation the number of marine battery modules are 286 which is equivalent to 839 car battery modules.

Module packaging in aluminium were assumed to be the inner boxes of the racks with a thickness of 1,5 mm. Consequently the battery retention and module fixings was removed in the car battery inventory. Battery cooling system were omitted on the batteries on board, as they are air cooled, and included in the ones at each pier.

Only a simple validation of the battery inventory scaling was carried out by looking at the total weight of the battery. The vessel battery pack has a weight of 10 tonne, and when only including these in the inventory the total battery weight were approximately 10 t (Siemens AS). This was justified as the largest environmental burdens in the manufacture of a battery were coupled to the battery cells manufacture and materials (Ellingsen et al., 2014).

5.3.3 Engine Production

The engine production was modelled by taking the weight of the engines multiplied by the typical weight composition of an engine provided by Wärtsilä (Wärtsilä, 2016). The main metal alloys are iron (90,8 %) and aluminium (2,7%) and carbon (2,2%) (Wärtsilä, 2016). As steel is consisted of iron and carbon, it was simplified that 91% of the mass of the engine was steel and 2,7% aluminium.

Two engine sizes were modelled as MF Oppedal needs a larger engine than the MS Ampere version on gas or diesel. The weight of the large engine was set to 4700 kg, equivalent to two Yanmar 6AYM-WET H-ration engines, and the small one had a total weight of 4300 kg, corresponding to two Cummins KTA 19 GC (Cummins Inc, 2009; Yanmar CO. LTD. Marine Operations Division, n.d.). Assuming only one engine used over the ferry life may underestimate the impacts as engines have extensive maintenance every 1200h run, where multiple parts are changed.

5.3.4 Electricity Consumption

In order to calculate the electricity consumption of the all-electrical ferry MS Ampere the transfer losses from electricity grid to battery had to be calculated. The shipping company Norled was contacted and Chief Technology Officer (CTO) Sigvald Breivik provided the following information:

- Losses in the chargers were around 4%
- Charging time is 9 minutes
- 1000 kW is charged from the shore battery
- 250 kW is charged from the electricity grid
- The mooring system requires a power of 7 kW

The efficiency of the battery through one cycle, charge and discharge, is 0,95 (Ellingsen, 2016). Figure 19 shows the grid to vessel-battery electricity distribution.

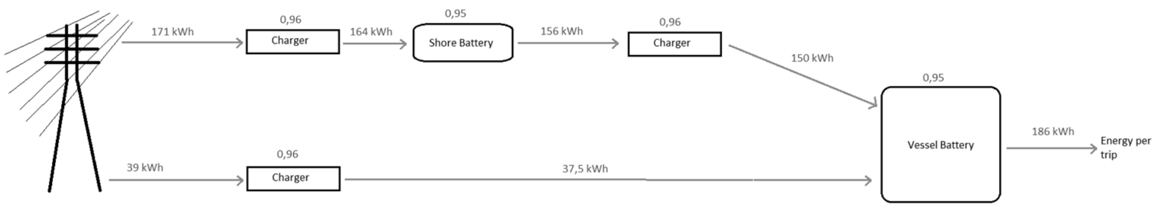


Figure 19: Grid to ferry electricity conversion with losses and energy.

On average the ferry has 186 kWh available per trip. This energy includes propulsion and auxiliaries. Energy consumed during night or when the charging hasn’t worked are not included. The energy consumed by the mooring system is around 1,2 kWh per trip.

In order to model the Norwegian electricity mix the process estimating Norwegian electricity supply mix in Ecoinvent is used. A supply mix is different from a production mix as it includes electricity trade between countries. The Norwegian electricity supply mix consists of 98% hydropower, compared to 99% hydropower in the production mix (Dones et al.). Impacts associated to the infrastructure is based on specific data on the Swiss distribution network. Infrastructure lifetime are estimated to 30-40 years and the copper requirements are 0,5 to 1,5 t/km conductor. Ecoinvent's modelling of the Norwegian supply mix is however in contradiction to the transactions of electricity where guarantees of origin can be purchased (The Norwegian Water Resources and Energy Directorate, 2015). Guarantees of origin will not be included in the present study.

The voltage was 616 V from the electricity grid according to Sigvald Breivik at Norled. Ecoinvent characterises electricity with less than 24 kV as low voltage, and the electricity was therefore categorised as low voltage (*Overview and Methodology*, 2007).

5.3.5 Diesel Consumption and Combustive Stressors

In order to determine the diesel consumption per trip for MS Oppedal the resistance was calculated. Guldhammmer and Harvalds, Hollenbach as well as model test data were used to estimate the resistance. The inputs used are presented in Table 7, with the source of the information.

Table 7: Principal information on MF Oppedal and source of information.

Dimension	Value	Unit	Information Source
Lightship	1705	ton	Sigvald Breivik, CTO Norled
payload	600	ton	Sigvald Breivik, CTO Norled
Volumetric displacement	2250	m^3	Estimated from lightship+payload
LOA	114,0	m	Sigvald Breivik, CTO Norled
LPP	104,9	m	ship-info.com
B	16,8	m	Sigvald Breivik, CTO Norled
T	3,4	m	Sigvald Breivik, CTO Norled
C_B	0,38	-	Calculated
S	1346	m^2	Estimated, using (Amdal et al., 2011)
Transit speed	11	kn	Sigvald Breivik, CTO Norled

Guldhammer and Harvalds method gave a total resistance of 59 kN, when proceeding through the method as described by Amdal et al. (Amdal et al., 2011). For Hollenbachs method a MATLAB script from the course TMR4247-Marine Technology-Hydrodynamics at Institute of Marine Technology were used. This gave a resistance of 65 kN. Professor Sverre Steen was consulted with these results and provided towing test results from MARINTEK on double ended ferries to acquire a more specific result (Pedersen, 2000). Coefficient of residual resistance specific for double ended ferries with one forward and aft azimuth thruster were taken from the study and the other resistance components were estimated using chapter 1.2 in Marine Technology 3 (Steen, 2013). This gave a resistance of 58kN at 11 kn that were used in the preceding calculations. Calculations for the different methods can be found in Appendix B – Resistance Calculations.

After determining the resistance of MF Oppedal, an operational profile of the ferry were estimated. Auxiliary needs were assumed to be 100 kW as used in Statens Vegvesen et al. for a 50 CEU ferry (Statens Vegvesen et al., 2016). Auxiliary needs for a 120 CEU ferry might be larger than for a smaller ferry, but assuming more efficient energy consumers on board makes this a reasonable estimate. A ferry is typically running at 50% of propulsion effect during manoeuvring, 120% during acceleration and 25% during retardation (Statens Vegvesen et al., 2016). The operational profile of MF Oppedal is presented in Figure 20.

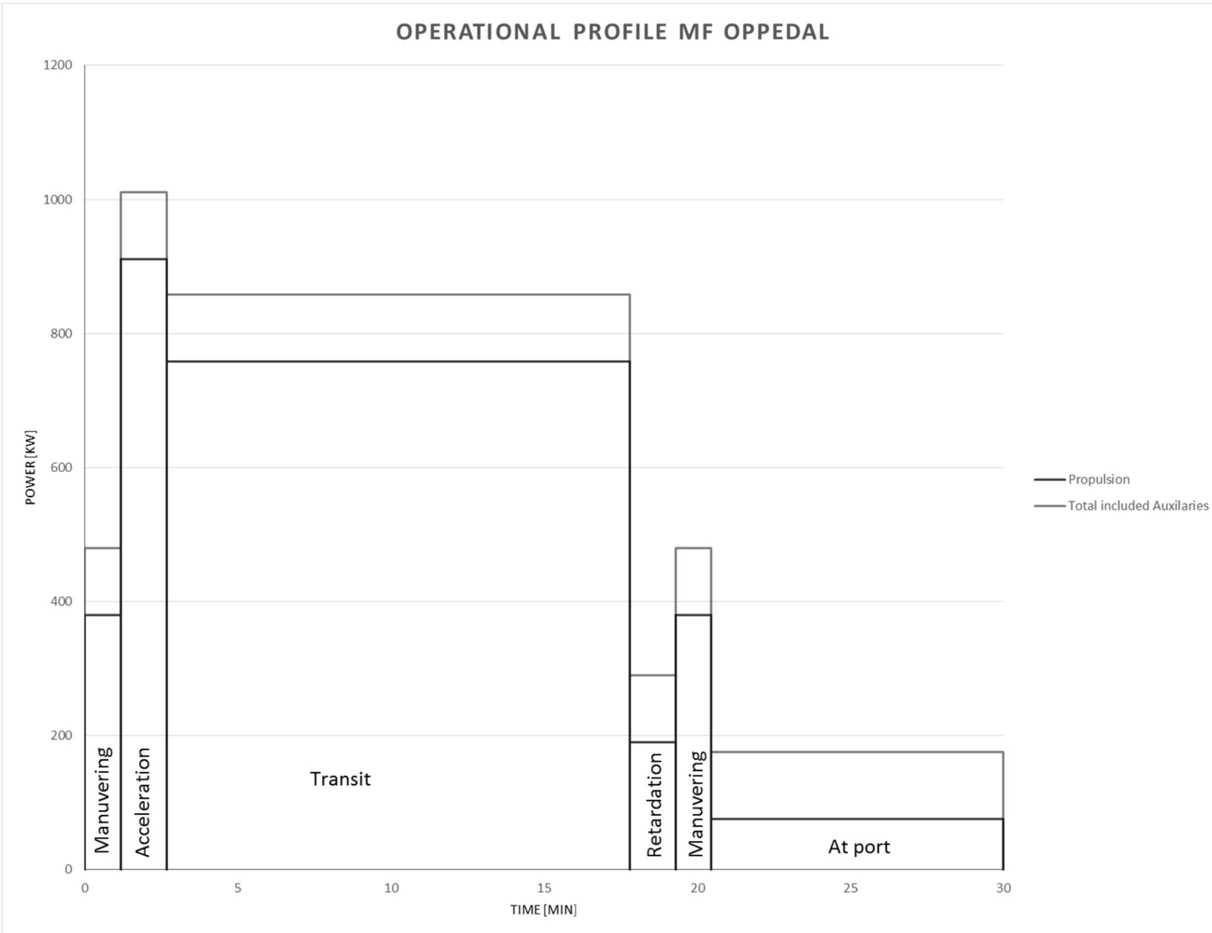


Figure 20: Operational profile MF Oppedal

With operational modes ranging from 175 – 1000 kW the desired engine should be flexible and allow the engines to run at 60-80% of maximum continuous power (MCR) as often as possible. Two generators of 500kW were considered a viable engine configuration for MF Oppedal. Variable speed generator sets were used as these provide state of the art emission characteristics. Specific fuel consumption data were gathered for engines of the desired size as a function of the rpm. It was assumed that two engines were run at all operational modes except at port. Specific fuel oil consumption was assumed to be 0,8 g/kWh. See Appendix C – Fuel

Consumption for further information and the calculations. The process "diesel, low sulphur at regional storage (average European)" were used in the Ecoinvent database. All steps from oil field exploration, crude oil production, long distance transportation, oil refining and regional distribution are estimated in the database (Dones et al.).

Combustive Stressors Diesel

Stressors covered in the third IMO GHG study was the combustive stressors included in the analysis (IMO, 2014). These are: $NO_x, CO_2, CO, SO_2, CH_4, N_2O$, PM (Particulate Matter) and NMVOC (Non-Methane Volatile Organics). For both ferries, MF Oppedal and the theoretical case MS Ampere running on diesel the same approach to calculating stressors have been applied.

NO_x emissions were estimated according to the IMO Tier II rule limits. The IMO tier – Regulation 13 applies to the Norwegian coast south of 62° and 4° west. Table 8 presents the calculation method.

Table 8: NOx rule calculation (IMO, 2016).

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016*	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

It can however be argued that the rule limits does not express an individual engines performance, and the NO_x emissions depend on the engine load not the rated speed (rpm). The calculated NO_x emissions may therefore be larger than the actual emissions from diesel combustion.

Emissions of CO_2,CO, SO_2, CH_4, $N_2O$and NMVOC were calculated using emission factors described in the third IMO GHG study (IMO, 2014). Emissions of CH_4 from diesel combustion is questioned in a report written by MARINTEK (SINTEF & MARINTEK, 2010). It is questioned whether these emission factors can come from instrument sensitivity due to exhaust pressure. Calculation of PM2,5 emissions were carried out using emission factors from the above mentioned report (SINTEF & MARINTEK, 2010). All stressors were modelled emitted in low population density areas. Emission factors are numbers giving the ratio between fuel consumed and the amount of a certain stressor being emitted. Table 9 presents the amount of different pollutants calculated per trips. In detail calculations can be found in Appendix D – Calculation of Combustive Stressors.

Table 9: Stressors calculated from diesel combustion per trip.

Ferry	MF Oppedal	Lightweight catamaran, MDO
Nox [kg]	3,21E+00	2,02E+00
CO2 [kg]	2,11E+02	1,30E+02
CO [kg]	1,82E-01	1,12E-01
SO2 [kg]	1,28E+01	7,90E+00
PM 2,5 [kg]	6,70E-02	6,06E-02
CH4 [kg]	3,94E-03	2,43E-03
N2O [kg]	9,86E-03	2,43E-03
NMVOC [kg]	2,02E-01	1,25E-01

5.3.6 Liquefied Natural Gas Consumption and Combustive Stressors

The same procedure as for the diesel ferries were used to estimate the fuel consumption of the theoretical MS Ampere on gas. A lean burn Otto cycle gas engine was chosen as this engine type is currently operated on ferries in Norway. The operational profile of MS Ampere is shown in Figure 21.

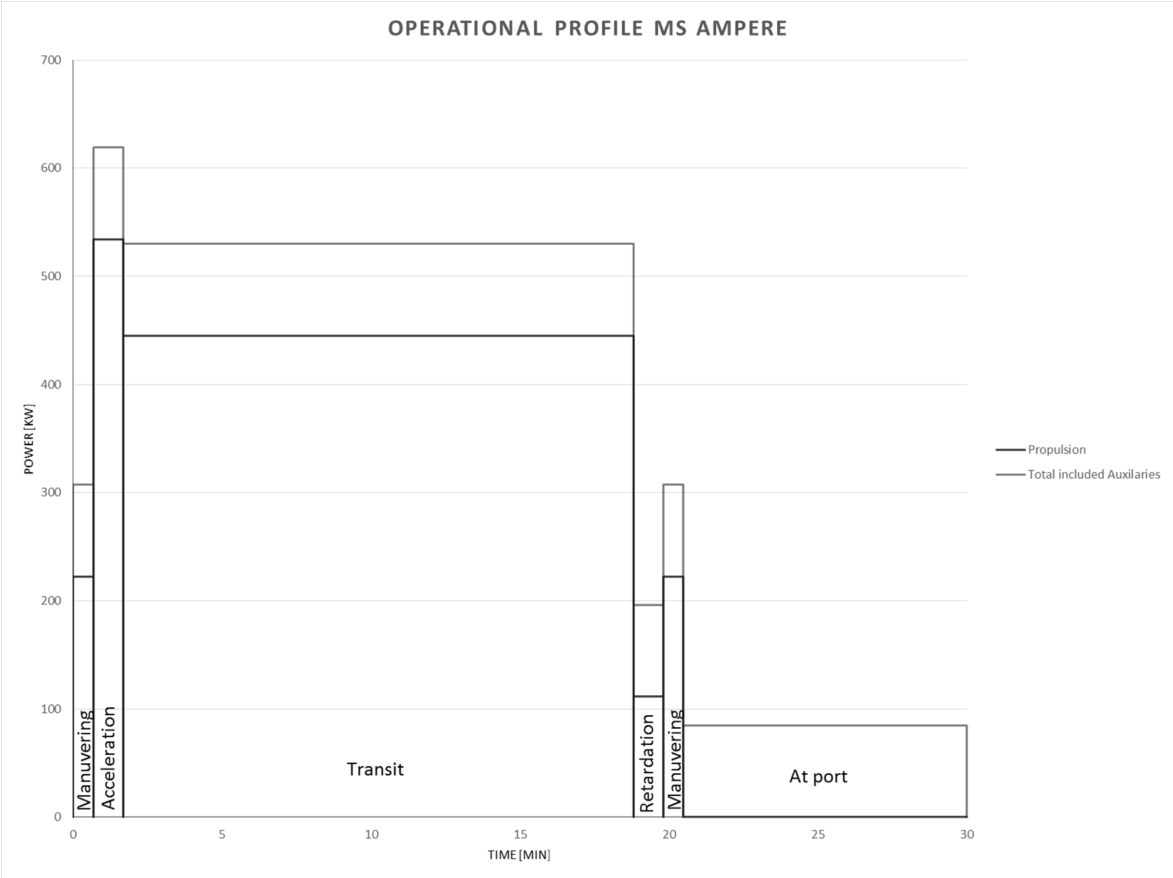


Figure 21: Operational profile MS Ampere.

This operational profile demands 80 – 600 kW power, and two generators of around 300 kW were therefore considered. MS Ampere running on gas or diesel is assumed to have electrical mooring system as MS Ampere run on batteries, giving only auxiliary power demand at port. Smaller gas engines have worse efficiency than larger gas engines, and a ferry with larger power demand might perform better compared to a diesel engine with the same size. The process "natural gas high pressure at the average European consumer" were used. Energy and material inputs to processes associated with gas field exploration, natural gas production, natural gas purification, long distance transport and regional distribution are estimated from data on the North Sea, Onshore in Germany, Algeria, Russia and Nigeria (Dones et al.).

Combustive Stressors LNG

Fuel consumption of LNG were calculated as the diesel engines, although the specific fuel consumption were given using MJ/kWh and not g/kWh. Emissions of NO_x and CH_4 were calculated using emission factors from a study by MARINTEK (SINTEF & MARINTEK, 2010). Amount of other stressors, CO_2, SO_2, $PM_{2,5}$, CO, N_2O and $NMVOC$ were calculated using emission factor from the third IMO GHG study (IMO, 2014). The amount of the different pollutants emitted per trip are presented in Table 10.

Table 10: Calculated stressors form combustion of LNG

Nox [kg]	2,57E-01
CO2 [kg]	1,26E+02
CO [kg]	3,59E-01
SO2 [kg]	9,18E-04
PM 2,5 [kg]	8,26E-03
CH4 [kg]	1,82E+00
N2O [kg]	5,05E-03

5.3.7 Other Operational Emissions

Zinc (Zn) anodes on the steel hull were included and it was assumed that all Zn was dissolved in ocean. The input form the background to the foreground of the amount of zinc required were set, as well as a stressor of the same amount of zink ions being released in the ocean. The CTO at Norled estimated 30 kg zinc used on a steel hull in five years. A steel hull will also require more surface paint to protect against corrosion, and the CTO at Norled estimated 100 l of paint used per year.

5.3.8 End of Life Hull

No direct data could be obtained on end of life treatment of hulls, only metal reuse was accounted for. This was done, as described in chapter II, by using secondary material as input for aluminium and partly secondary inputs in the steel for the steel hull.

5.3.9 End of Life Battery

The recycling of batteries are not included in the analysis, mostly due to lack of data. The following paragraph about future projections on recycling are taken from the researcher's project thesis.

The production of batteries is energy intensive, implying that dismantling them at the end of life will also be energy intensive (Dunn, Gaines, Kelly, James, & Gallagher, 2014). Energy intensiveness is on the other hand throughput dependent, and if more effective factories can be developed, effective recycling facilities are also plausible.

5.4 Impact Assessment

The ReCiPe midpoint quantification method were used as this is the one the researcher has the most experience with. Eighteen impact categories are addressed and these are:

- climate change [kg CO_2 eq.]
- ozone depletion [kg CFC-11 eq.]
- terrestrial acidification [kg SO_2 eq.]
- freshwater eutrophication [kg P eq.]
- marine eutrophication [kg N eq.]
- human toxicity [kg 1,4-DB eq.]
- photochemical oxidant formation [kg NMVOC]
- particulate matter formation [PM_{10} eq.]
- terrestrial ecotoxicity [kg 1,4-DB eq.]
- freshwater ecotoxicity [kg 1,4-DB eq.]
- marine ecotoxicity [kg 1,4 DB eq.]
- ionising radiation [kg U235 eq.]
- agricultural land occupation [m^2]
- urban land occupation [m^2]
- natural land transformation [m^2]
- water depletion [m^3]
- mineral resource depletion [kg Fe eq.]
- fossil fuel depletion [kg oil eq.]

The viewpoint most commonly used are the hierarchist, but it could also be argued to use individualist or egalitarian viewpoint as the lifetime of the ferry is only 30 years although it has emissions contributing to long term environmental impacts.

6 Results

The midpoint results, quantified impacts in a certain category quantified in a certain stressor type, will be presented in the following chapter using the ReCiPe impact assessment method. MS Ampere will be referred to as the all-electric or electric ferry, in some plots el. MF Oppedal is presented as the conventional ferry and the two theoretical cases of MS Ampere will be presented as diesel and gas or MDO and LNG.

Total impacts, the D_{tot} vector for this analysis is presented in Table 11. All impact categories in ReCiPe are included, as the researcher considers all categories relevant in order to provide a holistic set of results. The hierarchist viewpoint is presented in Table 11, while the D_{tot} for egalitarian and individualist viewpoints are given in Appendix E – Vector of Total Impacts Egalitarian and Individualist. Results are per crossing, as this was set as the functional unit in chapter 5.2.1

Table 11: Total impacts for the ferry options in all impact categories per crossing.

Hierarchist	unit	EL-ferry	Conv	Gas	Diesel
Agricultural land occupation	m2a	5,12E-01	2,41E-01	5,97E-02	1,14E-01
Climate change	kg CO2 eq	6,58E+00	2,58E+02	2,02E+02	1,57E+02
Fossil depletion	kg oil eq	1,58E+00	8,23E+01	6,26E+01	5,01E+01
Freshwater ecotoxicity	kg 1,4-DB eq	4,12E-01	3,06E-01	4,78E-02	1,45E-01
Freshwater eutrophication	kg P eq	1,23E-02	8,05E-03	1,66E-03	4,37E-03
Human toxicity	kg 1,4-DB eq	2,48E+01	1,02E+01	2,63E+00	6,04E+00
Ionising radiation	kg U235 eq	1,73E+00	5,35E+00	5,31E-01	3,03E+00
Marine ecotoxicity	kg 1,4-DB eq	4,35E-01	3,42E-01	8,81E-02	1,51E-01
Marine eutrophication	kg N eq	4,28E-03	1,34E-01	1,26E-02	8,38E-02
Metal depletion	kg Fe eq	7,35E+00	7,35E+00	9,49E-01	1,03E+00
Natural land transformation	m2	3,16E-03	9,01E-02	3,73E-02	5,53E-02
Ozone depletion	kg CFC-11 eq	4,33E-07	3,79E-05	2,42E-05	2,33E-05
Particulate matter formation	kg PM10 eq	2,23E-02	3,48E+00	9,27E-02	2,14E+00
Photochemical oxidant formation	kg NMVOC	2,45E-02	4,79E+00	5,43E-01	2,98E+00
Terrestrial acidification	kg SO2 eq	5,24E-02	1,49E+01	2,35E-01	9,21E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	6,79E-03	1,50E-02	2,86E-03	9,05E-03
Urban land occupation	m2a	9,62E-02	4,29E-01	7,27E-02	2,54E-01
Water depletion	m3	2,39E+02	7,58E+01	9,56E+00	3,34E+01

Figure 22 shows a 100% stacked bar chart for all options and impact categories divided on foreground and background processes. Foreground is processes that are modelled by and has data collected or calculated by the researcher. Background processes are often inputs to the foreground where generic databases have been used.

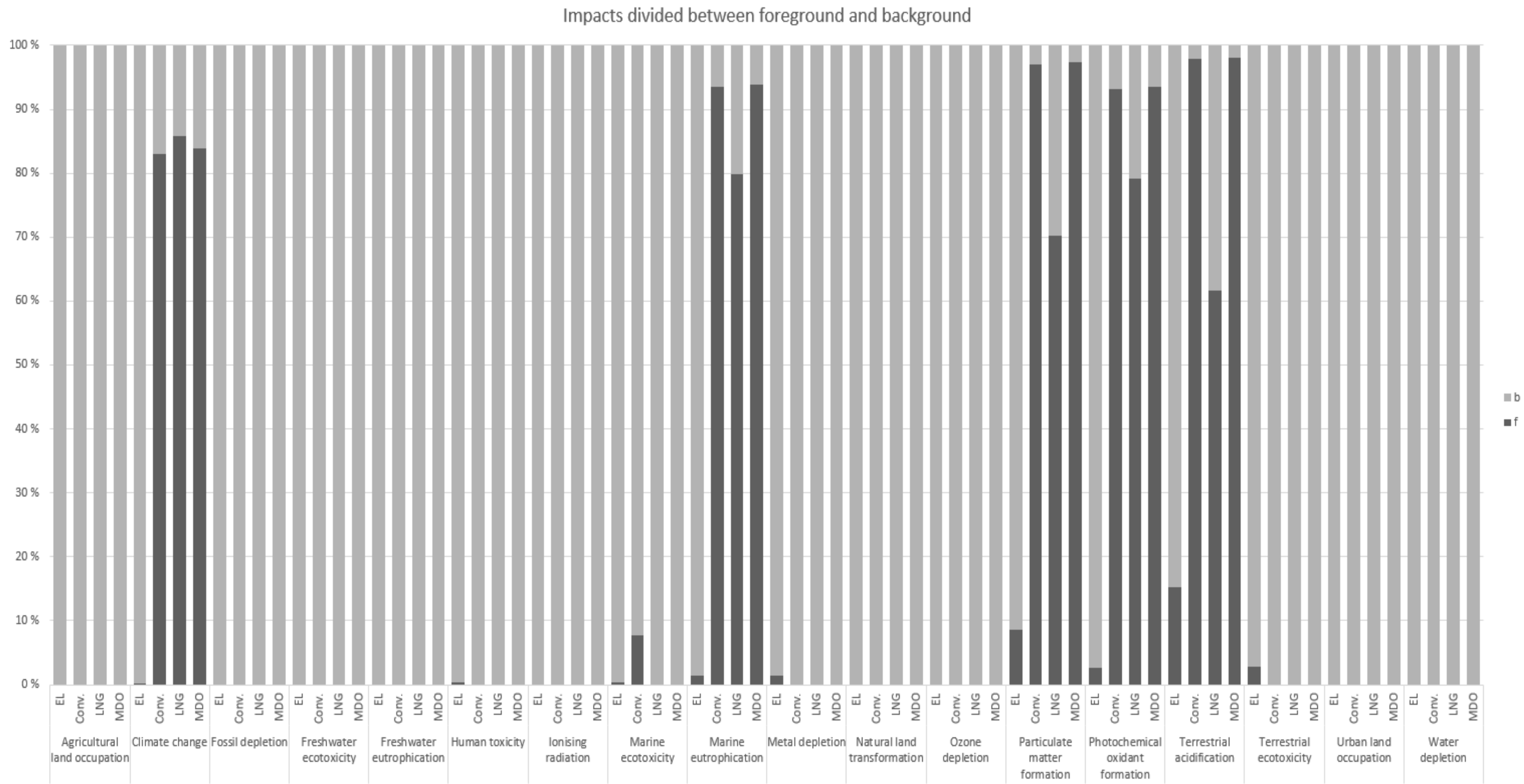


Figure 22: 100% bar chart for all ferry options and impact categories divided on foreground (dark) and background (light).

Figure 22 illustrates that for all impact categories except climate change, marine eutrophication, particulate matter formation, photochemical oxidant formation, terrestrial acidification the background processes are dominating the impacts for most ferries.

A detailed graphical representation of all categories were also made. These will be presented in the next chapters for the hierarchist viewpoint. The impacts are also divided between the processes operation, hull production and battery or engine production to provide more specific insight to the results. It should also be noted that impact categories with the same unit will be displayed with different axes to properly illustrate the components in the following chapters.

6.1 Land Use

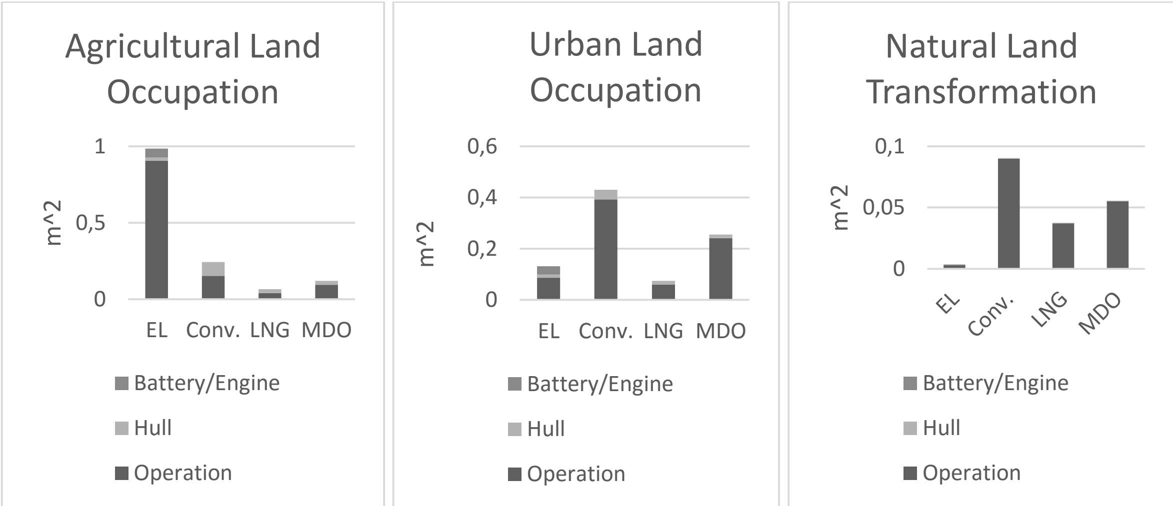


Figure 23: Land use divided on the different ferry alternatives.

Land use are dominated by impacts stemming from operation as shown in Figure 23. The electrical ferry have the largest impact in the category agricultural land occupation mostly due to wood materials used in the electricity distribution network. The diesel ferries have the largest occupation of urban land due to onshore production plants. The conventional ferry has the largest impacts on natural land transformation caused by well exploration and production of oil onshore, and this impact is 27 times the impact of the electrical ferry which has the least impact in this category.

6.2 Climate Change

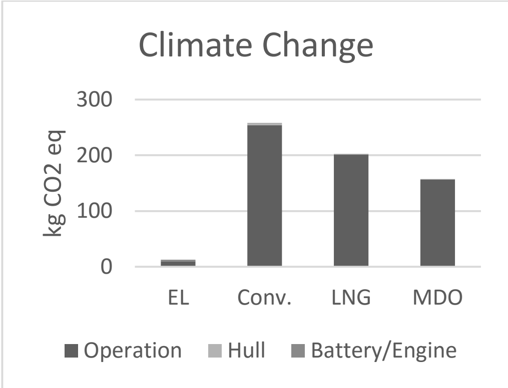


Figure 24: Climate change impacts for the different ferry options.

Figure 24 shows that the conventional ferry has the largest impact in the climate change category before LNG, MDO and the electrical ferry. Operation has the largest contribution to the category for all alternatives, although the batteries contribute to 40% of the impacts associated with the electrical ferry.

6.3 Resource Depletion

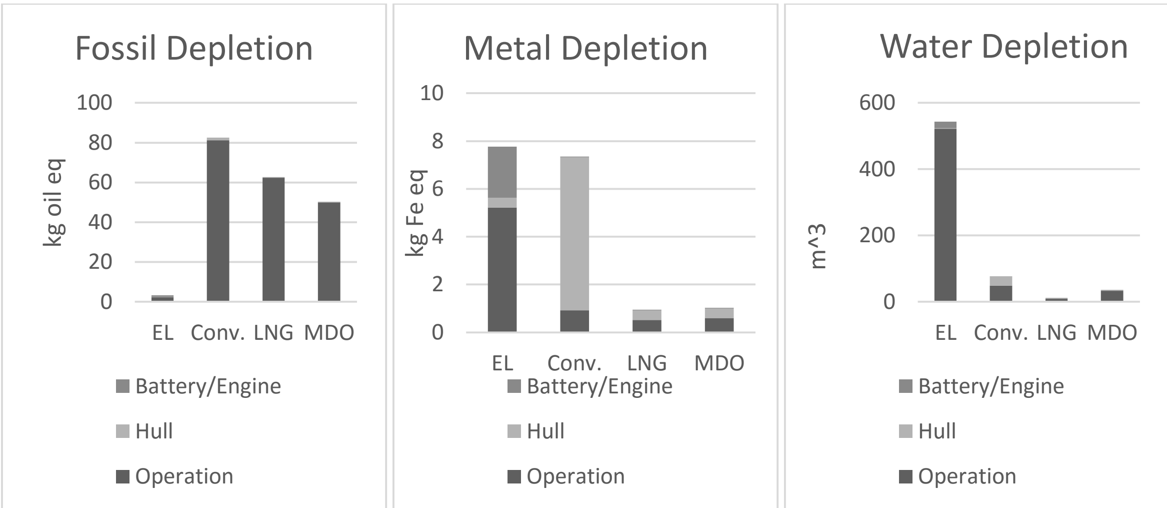


Figure 25: Resource depletion for the different ferry options

Figure 25 shows that operation contributes to the largest depletion of the three resources except metal depletion for the conventional ferry and fossil depletion for the electrical ferry. The electrical ferry is around 50, 35 and 30 times better in fossil depletion than the conventional, gas and diesel ferry.

The electrical and the conventional ferry have the largest impacts on metal depletion. For the electrical ferry the largest contributors are operation (electricity distribution grid Cu) and the battery (Cu for anode), while the hull has the largest contribution for the conventional ferry. LNG and MDO ferries are around eight times less metal depleting than the electrical ferry.

The electrical ferry has the largest water depletion potential, from operation, and hydroelectricity in the Norwegian electricity mix explain this. The conventional ferry has the second largest impact, while the lightweight diesel has the third largest impacts and the LNG option has the least impacts in this category.

6.4 Toxicity

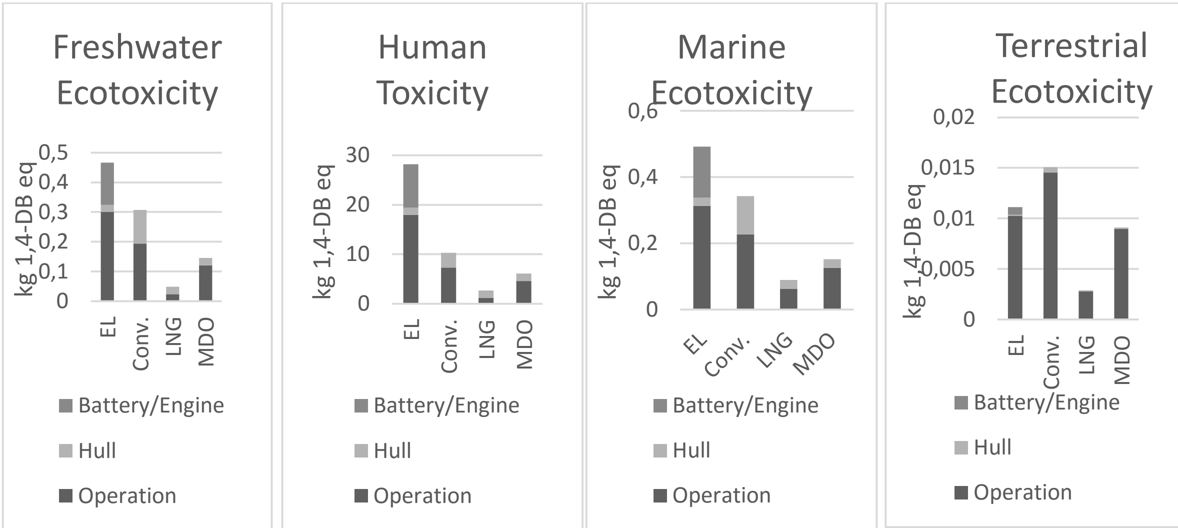


Figure 26: Toxicity impacts for the different ferry options.

As shown in Figure 26 the electrical ferry has the largest impact in all toxicity categories except terrestrial ecotoxicity where the conventional ferry has the largest impacts. Extraction of metals, especially copper, lead to disposal of sulfidic tailings which has a major contribution to the toxic impacts associated with the electrical ferry. The conventional ferry has the largest impact in terrestrial ecotoxicity due to drilling waste from onshore diesel production. The LNG driven ferry has the smallest impact in all toxicity categories.

6.5 Eutrophication

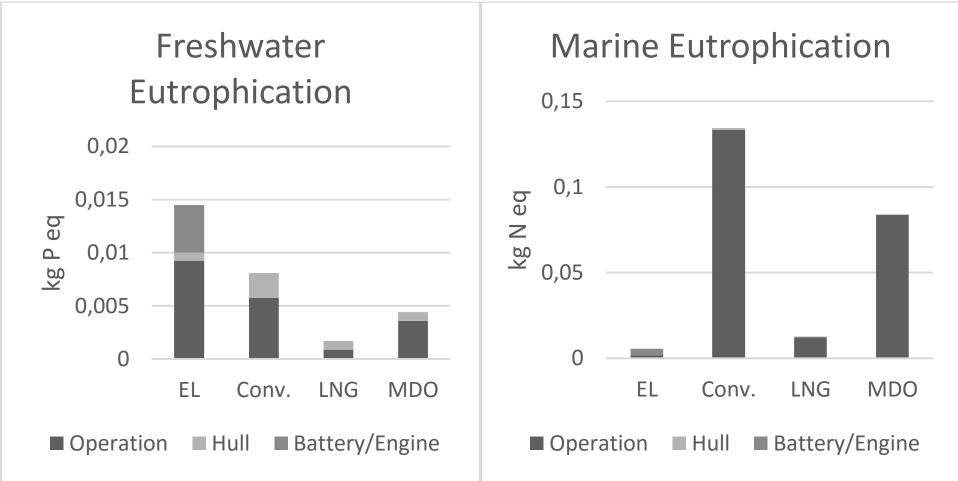


Figure 27: Eutrophication impact for the different ferry options.

The electrical ferry has the largest impact in freshwater eutrophication, as shown in Figure 27. This is mostly due to copper extraction for the electricity distribution network and anode material for the battery. The operational phase has the largest impact for all ferry options. In marine eutrophication the conventional ferry has the largest impact and the lightweight option run on diesel has the second largest impact, due to emissions of NO_x from combustion.

6.6 Ionising Radiation

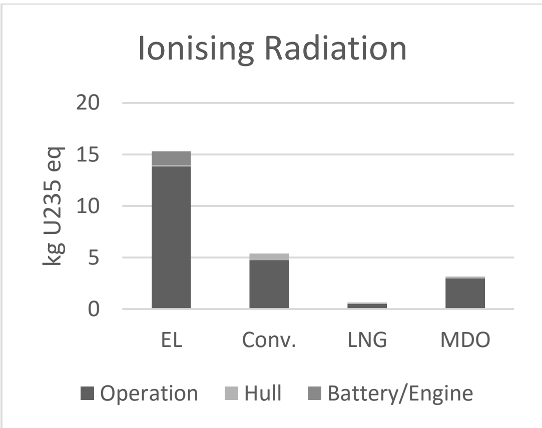


Figure 28: Ionising radiation impacts for the different ferry options.

Figure 28 displays that the electrical ferry has the largest impact in the category ionising radiation due to Swedish nuclear power in the Norwegian supply mix of electricity.

6.7 Ozone Depletion

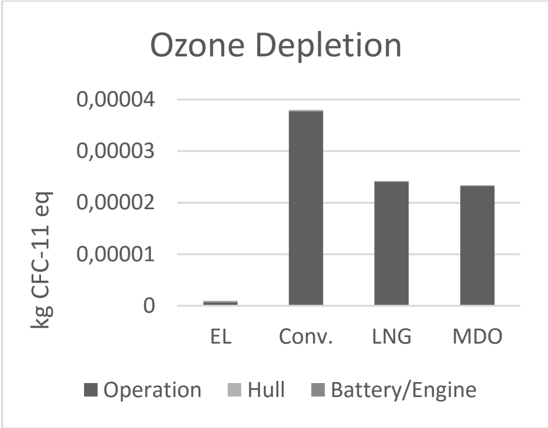


Figure 29: Ozone depletion impacts for the different ferry alternatives.

Figure 29 displays the ozone depletion impacts of the different ferry options. The ferries run on fossil fuel has larger impacts on ozone depletion due to production of fossil fuels than the electrical ferry.

6.8 Particulate Matter Formation

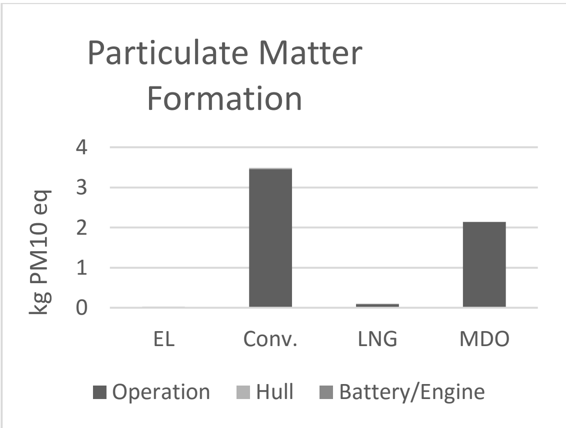


Figure 30: Particulate matter formation impacts for the ferry cases.

Figure 30 illustrates that ferries run on diesel gives larger formation of particulate matter, 145 and 89 times worse than the electrical ferry for the conventional and lightweight options respectively. The LNG option has three times larger impacts than the electrical ferry. Operation is dominating the impacts.

6.9 Photochemical Oxidant Formation

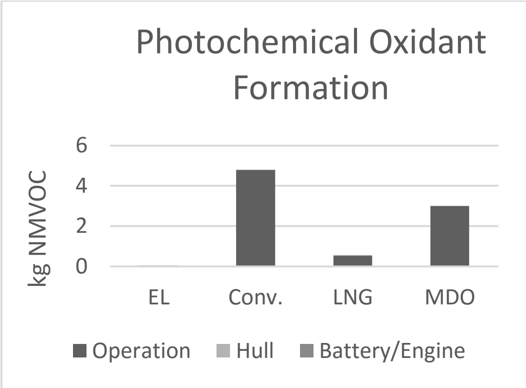


Figure 31: Photochemical oxidant formation for the ferry cases.

Figure 31 displays the photochemical oxidant formation for the different ferry options. The diesel ferries also contribute to the largest formation of photochemical oxidants, and the conventional and lightweight diesel is 180 and 110 times worse than the electrical ferry. The LNG ferry is 20 times worse than the electrical ferry.

6.10 Terrestrial Acidification

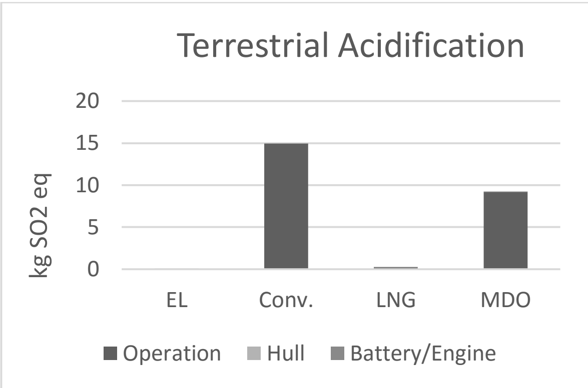


Figure 32: Terrestrial acidification impacts for the different ferries.

Figure 32 shows that ferries run on diesel containing sulphur have larger impact on terrestrial acidification than fuels not containing sulphur. LNG will have small sulphur emissions due to lubricating oil. The improvement factor an electrical ferry offers is 260, 3 and 160 for the conventional, LNG and lightweight diesel ferry.

6.11 Summary of the Results

The electrical ferry outperforms the other alternatives in the following seven categories;

- Climate change
- Fossil depletion
- Marine eutrophication
- Natural land transformation
- Ozone Depletion
- Particulate matter formation
- Photochemical oxidant formation

This is not surprising as these categories are largely affected by stressors stemming from combustion or production of fossil fuel. The all-electric ferry has the advantage of limited usage of fossil fuels.

The electrical ferry is on the other hand the alternative that performs worst in the following seven categories;

- Agricultural land occupation
- Freshwater ecotoxicity
- Freshwater eutrophication
- Human toxicity
- Ionising radiation
- Marine ecotoxicity
- Metal depletion
- Water depletion

For all these impact categories the operational phase has the largest contribution, and for an electrical ferry this is caused by electricity consumption. The electricity network demands inputs in terms of wooden materials, copper, nuclear and hydropower to produce and supply electricity. Especially the extraction of copper leading to sulfidic tailings contribute across several impact categories regarding toxicity and freshwater eutrophication.

The LNG ferry performs best in nine categories;

- Agricultural land occupation
- Freshwater ecotoxicity
- Freshwater eutrophication
- Human toxicity
- Ionising radiation
- Metal depletion
- Terrestrial ecotoxicity
- Urban land occupation
- Water depletion

The LNG option does not perform worst in any categories, while the diesel options never performs best in any categories. The conventional ferry is always outperformed by the lightweight diesel option.

7 Discussion

The present study have calculated and presented all impact categories in ReCiPe for four different ferry alternatives. It shows a holistic evaluation of the environmental impacts of all-electrical ferries compared to ferries run on fossil fuels. In this chapter the main results will be discussed before subchapters are presented. The subchapters consists of a qualitative assessment of the data, a comparison to other studies, a sensitivity analysis and an evaluation of the feasibility of the theoretical ferry cases.

A problem shift from reduction of impacts in categories linked to fossil fuels and increases in many categories regarding toxicity is identified. This is a similar trend as electrical cars where the increase in human toxicity have been estimated to lie between 180-290% (Hawkins et al., 2013). The present study observe increases in human toxicity of 170-400% for ferries, dependent on whether the conventional ferry or lightweight design run on MDO is used as baseline. Extraction of copper leading to the disposal of sulfidic tailings are the main contributor to the toxicity impacts. Copper is mainly used in the electricity distribution network and in the battery. For the conventional ferries no specific process besides the production and usage of fossil fuels are contributing largely in any impact categories. This implies that the measures to reduce impacts from electrical and conventional ferries are different. To reduce impacts from all-electric ferries the material inputs must be adjusted by either using more secondary inputs or decrease the impacts coupled to mining activities. For ferries run on fossil fuels decreasing impacts associated with fossil fuel extraction and production can reduce impacts and a measure that can have effects on all ferry alternatives are reduction of power consumption.

The findings can increase policymakers understanding of the environmental impacts of different ferry options. Highlighting the fact that optimizing one impact category often gives increases in other impact categories or in processes outside the system is important. In the resent study the global impacts of climate change are replaced with local concerns of toxicity.

For the policymakers and ferry operators the present study and future studies within the field can give insights to where the impacts are largest and hence where the largest reductions can be obtained. This analysis has not included emission reducing technologies such as scrubbers or catalysts. Future studies should attempt to include such measures as well as more fuel and engine configurations such as hybrid options and hydrogen. Varying design solutions and operational parameters, for example length of crossing, speed, hull form and material would improve the applicability of the study. This would indicate for what ferry route different ferry options should be chosen. Also what state of the art emission reducing technology should be used.

For suppliers in this market the present study and future studies can give some insight to what components that pose the largest environmental impact. If companies themselves provided this information or carried out an LCA on single components in a holistic manner a more complete and accurate study could be presented and be less time consuming to execute.

Operation has the largest contribution for most impact categories, and in production of the electrical ferry the batteries have substantially larger impacts than the materials used in the hull. The batteries have more than 20% of the total impacts for the electrical ferry in 12 impact categories. Marine Eutrophication is the only impact category where the battery has larger impacts than 50% of the total. End of life is omitted in the present study, and future studies should strive to include this in the analysis. This is suspected to influence the results of the all-electrical ferry more than the ones run of fossil fuels due to recycling of batteries. Less impacts in metal depletion is expected, though more energy is required for the recycling process itself.

The model does not reflect the entire ferries but some of the components and parts of the operation of them. Only material for hull and engines, battery production and some operational inputs are included in the analysis. This can have larger impact for ferry cases and impact categories where the total impacts are small and increases in impacts can have large effects. Production for example has a larger share of climate change impacts for the electrical ferry than for the conventional ferries.

7.1 Data Quality

Data estimation, collection and structuring were described in chapter 0, and several methods of acquiring data have been used and they therefore have different quality. Consolidation of experts, data estimation, literature, generic databases and a combination of these have been used to estimate the inputs to the analysis.

Experts have contributed with the amount of hull material, zinc anodes, paint and guidance of the researcher in scaling battery data, resistance calculations and stressor calculations. Data estimation have been carried out by the researcher and most values obtained were used as the amount of a certain process in the Ecoinvent database.

As described in chapter 0 the inputs of primary copper to the electricity distribution network as well as upstream processes in the processing of fossil fuels had large impacts in certain categories. This might indicate that the choice of database processes have large impacts on the results and these effects are difficult to investigate without further insight to the Ecoinvent database. For the electrical ferry impacts associated to copper extraction leading to sulfidic tailings give large impacts in toxicity. Consequences can be that the background processes used does not match the intended purpose, the model is incomplete and the fact that the interpretation of the results is limited.

It has been attempted to have the same data quality on the systems that were compared, but some exceptions have been made. These are the raw material input for steel and aluminium and the level of detail in the data for the battery compared to the engines. This can however be justified by the level of impact the parameters have on the results.

In most cases, except for metal depletion, the hull does not contribute largely to the end impact, and the Ecoinvent database only have secondary aluminium and not steel as a process. Pig iron, with a recycled scrap content of 35% were therefore chosen as this were the steel that had the largest recycling fraction. It could be argued that instead of using different amounts of recycled inputs primary aluminium and steel should be used as input, and the recycling should be modelled in the model as separate processes. The modelling of recycling were however considered too time consuming as there are substantial differences and factors that should be taken into account. Some of these are the level of recycling of the subsequent materials in a ferry, the difference in melting temperature and the difference in removable alloying elements. Another input to the discussion is the fact that there is not large enough supply for secondary aluminium to support more than 20-25% of the current demand (Hydro, 2012).

Specific data have been used to estimate the production impacts of the batteries, compared to the engines there simplified and unspecific data have been used. More batteries are used over the vessel life than conventional engines, and the difference in level of detail for the battery and engine can therefore be justified.

7.2 Comparison to Studies within the Field

In this chapter the results obtained in the present study are compared to the ones presented by Statens Vegvesen, Siemens and Bellona as well as Corvus Energy.

In the study by Statens Vegvevsen investigating energy efficiency and climate consequences for ferry operation one of the functional units used were gram CO_2 per CEU-km (Statens Vegvesen et al., 2016). Table 12 presents the results of this analysis converted to gram CO_2 equivalents per CEU-km as well as the results from Statens Vegvesen. Statens Vegvesen does not present all results for a ferry with 120 CEU and when contacted about accessing the data tool developed in the study this tool were defined as “not public”. Therefore different sizes closest to 120 CEU is presented in Table 12 and the difference and ranking of the alternatives will be looked at. Statens Vegvesen also looks at a ferry crossing of 6,8 km which is longer than Lavik-Oppedal which is 5,6km, this can imply that the results from Statens Vegvesen might be smaller than the ones of this study due to increased time in transit mode. The number of crossings is similar for all results presented.

Table 12: Comparison of results from the present study and the ones presented by Statens Vegvesen.

Energy carrier	Hull type, material	Capacity [CEU]	Speed [kn]	Results of this study [g CO2 eq./ CEU-km]	Statens Vegvesen [g CO2 eq./CEU-km] (Statens Vegvesen et al., 2016)	Comment
EL	catamaran, al	120	10	10	-	
EL	?	125	10	-	31	
Diesel	monohull, steel	120	10	383	327	Statens Vegvesen is looking at diesel mechanical, while the other result is for diesel electric
Diesel	catamaran, al	120	10	233	-	
LNG	catamaran, al	120	10	301	-	
Diesel	monohull, steel	70	10	-	353	
Diesel	catamaran, al	70	10	-	375	
LNG	catamaran, al	70	10	-	379	
EL	catamaran, al	70	10	-	38	

A comparison of the selection that are of almost equal size reveals some differences in the magnitude of the results. For an all-electric ferry with capacity of 125 CEU Statens Vegvesen calculates 31 g CO_2 per CEU-km. The present study calculated 10 g CO_2 equivalents per CEU-km. This difference is somewhat difficult to explain as no transparent inventory of the Statens Vegvesen et al. is available. GWP from 1 kWh of electricity is however provided and the value used is the demand for the tender, 75 g CO_2 equivalents per kWh, which is substantially larger than the values used in the present study. It uses around 44 g CO_2 equivalents per kWh. It was therefore attempted to use the same impact from electricity as Statens Vegvesen et al. and this gave 28 g CO_2 equivalents per CEU-km, which is similar to Statens Vegvesen et al. for a ferry with 5 more CEU than MS Ampere which has 31 g CO_2 equivalents per CEU-km.

For a monohull in steel, the answers for diesel electric and mechanical were compared, and the ferries had the same capacity of 120 CEU. Statens Vegvesen calculated 327 g CO_2 per CEU-km and the results of this study gives 383. This is can be explained by the fact that Statens Vegvesen has a longer crossing and fewer losses due to diesel mechanical operation.

The answers are in the same order of magnitude, and gives an indication of a somewhat valid analysis.

The 70 CEU alternatives were included as this were the only results covering similar options to the ones included in this analysis. LNG and two diesel options were nine to ten times worse than the electrical ferry, which is a smaller difference than 22-36 which were difference between fossil driven and electrical presented in chapter 0, in the impact category climate change. The main explanation for this is the fact that the climate change impact for the electrical ferry is substantially smaller in this study than for Statens Vegvesen. The internal ranking is also different, and Statens Vegvesen classifies the catamaran LNG as the worst option, then the diesel catamaran, then the diesel monohull in steel before the all-electric catamaran ferry. This can also indicate that the resistance of MS Ampere is substantially lower than the catamaran design used as a basis by Statens Vegvesen. LNG is in both studies pointed out as having larger CO_2 footprint than an equal design run on diesel. Statens Vegvesen does not specify what time horizon the results are given for making the comparison somewhat unspecific.

Other studies on electrical ferries reports the amount of CO_2, fuel and NO_x abated by switching to electrical ferries. Siemens and Bellona and the battery manufacturer Corvus Energy have published such results with MS Ampere as a starting point (Bellona & Siemens AS, 2015; Corvus Energy, 2016b). It is not specified what type of ferries the electrical one is compared to, but if MF Oppedal going the same number of trips as MS Ampere is used the results are very similar. This is presented in Table 13. As the results are converted to the amount abated by operation of one conventional ferry for one year. Stressors calculated in chapter 0 are the numbers up for comparison in Table 13.

Table 13: Comparison of fuel consumption, CO_2 and NOx.

	Stressors from chapter 5.3.5	Siemens & Bellona (Bellona & Siemens AS, 2015)	Corvus Energy (Corvus Energy, 2016b)
CO2 [ton/year]	2500	2400	2680
Fuel [ton/year]	790	790	890
NOx [ton/year]	40	60	37

All numbers presented in Table 13 are in the same order of magnitude and indicates that realistic input has been used in the analysis if the two options compared are similar to MS Ampere and MF Oppedal. Smaller reductions would be obtained if the diesel version of MS Ampere were used, and the savings are presented in Table 14.

Table 14: Abated fuel consumption, CO_2 and NOx by using MS Ampere diesel version.

	Stressors from chapter 5.3.5, MDO Ampere
CO2 [ton/year]	1600
Fuel [ton/year]	500
NOx [ton/year]	25

This imply that the studies conducted by Siemens & Bellona and Corvus Energy have chosen an option where the all-electric ferry appear to have larger reduction potential than if a more similar solution were chosen.

7.3 Sensitivity of Results

A sensitivity analysis are looking into the dependencies between the results and input to the analysis. This chapter presents the difference in using the ferry capacity and the ferry load as the functional unit as well as the variability in the results when varying specific input parameters that were considered relevant.

7.3.1 Using Capacity or Average Freight

In order to compare car-ferry transport to other modes of transport the functional unit of capacity or average load per km is useful. These results are presented in Table 15 and Table 16. Results increase by a factor of 3,29 when using the average load instead of the ferry capacity. This can imply that the footprint of ferry transport are larger than the ones where capacity are used due to the fact that the ferries are not fully utilized. Rush hour or holyday traffic are however peaks in the flow of traffic, and having to keep the waiting time as low as possible mean that the ferries cannot be fully utilized at all times.

Table 15: D_tot per CEU-km using capacity.

Hierarchist	unit	EL-ferry	Conv	Gas	MDO
Agricultural land occupation	m2a	1,47E-03	3,59E-04	9,27E-05	1,73E-04
Climate change	kg CO2 eq	1,88E-02	3,83E-01	3,01E-01	2,33E-01
Fossil depletion	kg oil eq	4,82E-03	1,23E-01	9,32E-02	7,46E-02
Freshwater ecotoxicity	kg 1,4-DB eq	6,94E-04	4,56E-04	7,13E-05	2,16E-04
Freshwater eutrophication	kg P eq	2,15E-05	1,20E-05	2,48E-06	6,52E-06
Human toxicity	kg 1,4-DB eq	4,20E-02	1,52E-02	3,93E-03	9,00E-03
Ionising radiation	kg U235 eq	2,28E-02	7,96E-03	8,99E-04	4,62E-03
Marine ecotoxicity	kg 1,4-DB eq	7,32E-04	5,09E-04	1,31E-04	2,25E-04
Marine eutrophication	kg N eq	8,44E-06	2,00E-04	1,87E-05	1,25E-04
Metal depletion	kg Fe eq	1,16E-02	1,09E-02	1,41E-03	1,54E-03
Natural land transformation	m2	5,63E-06	1,34E-04	5,55E-05	8,24E-05
Ozone depletion	kg CFC-11 eq	1,36E-09	5,65E-08	3,59E-08	3,47E-08
Particulate matter formation	kg PM10 eq	4,64E-05	5,17E-03	1,38E-04	3,19E-03
Photochemical oxidant formation	kg NMVOC	5,54E-05	7,13E-03	8,08E-04	4,44E-03
Terrestrial acidification	kg SO2 eq	1,08E-04	2,22E-02	3,50E-04	1,37E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	1,65E-05	2,23E-05	4,29E-06	1,35E-05
Urban land occupation	m2a	1,96E-04	6,39E-04	1,08E-04	3,78E-04
Water depletion	m3	8,09E-01	1,13E-01	1,67E-02	5,21E-02

Table 16: D_tot using average load.

Hierarchist	unit	EL-ferry	Conv	Gas	Diesel
Agricultural land occupation	m2a	6,28E-03	1,54E-03	3,97E-04	7,42E-04
Climate change	kg CO2 eq	8,04E-02	1,64E+0 0	1,29E+0 0	1,00E+00
Fossil depletion	kg oil eq	2,06E-02	5,25E-01	3,99E-01	3,20E-01
Freshwater ecotoxicity	kg 1,4-DB eq	2,97E-03	1,95E-03	3,06E-04	9,26E-04
Freshwater eutrophication	kg P eq	9,23E-05	5,13E-05	1,06E-05	2,79E-05
Human toxicity	kg 1,4-DB eq	1,80E-01	6,52E-02	1,69E-02	3,86E-02
Ionising radiation	kg U235 eq	9,76E-02	3,41E-02	3,85E-03	1,98E-02
Marine ecotoxicity	kg 1,4-DB eq	3,14E-03	2,18E-03	5,63E-04	9,64E-04
Marine eutrophication	kg N eq	3,62E-05	8,55E-04	8,01E-05	5,34E-04
Metal depletion	kg Fe eq	4,95E-02	4,69E-02	6,06E-03	6,58E-03
Natural land transformation	m2	2,41E-05	5,75E-04	2,38E-04	3,53E-04
Ozone depletion	kg CFC-11 eq	5,84E-09	2,42E-07	1,54E-07	1,49E-07
Particulate matter formation	kg PM10 eq	1,99E-04	2,22E-02	5,91E-04	1,37E-02
Photochemical oxidant formation	kg NMVOC	2,37E-04	3,06E-02	3,46E-03	1,90E-02
Terrestrial acidification	kg SO2 eq	4,64E-04	9,53E-02	1,50E-03	5,88E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	7,09E-05	9,57E-05	1,84E-05	5,78E-05
Urban land occupation	m2a	8,38E-04	2,74E-03	4,65E-04	1,62E-03
Water depletion	m3	3,47E+0 0	4,84E-01	7,16E-02	2,23E-01

The GWP attributed to transport of one CEU one km is therefore 20 or 80 g CO_2 dependent on whether the capacity of the all-electric ferry, assuming it is fully loaded at all times, or average number of CEU is transported. It would be interesting to compare these numbers to other transport modes, but the common unit used is ton-km. GWP for different surface transport modes are presented in Figure 33.

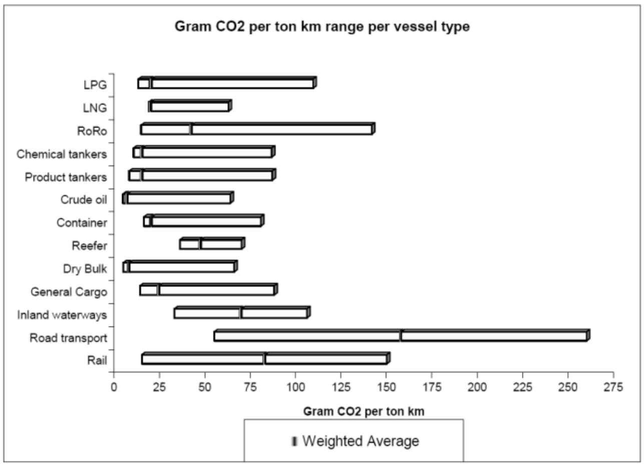


Figure 33: CO2 footprint from different surface transport modes (Lindstad, Asbjørnslett, & Pedersen, 2012)

Assuming that one CEU has the weight of 1,5 tonne gives the electrical ferry a CO_2 footprint of approximately 10 or 50 g CO_2 per ton-km. If the conversion between CEU-km and ton-km is somewhat valid the electrical ferry has less impacts than the average rail, road and inland waterway transport.

7.3.2 Varying Input Parameters

Impact of the different perspectives, difference in crossings per lifetime, battery life, electricity mix and metal inputs for production of hull and engines were investigated.

Difference in Viewpoint

D_tot was examined for all viewpoints, and the viewpoint had little impact on ranking of the three alternatives except in the categories global warming, human toxicity, marine ecotoxicity and terrestrial ecotoxicity. For global warming the individualist favoured the conventional ferry over the LNG alternative, meaning that two worst alternatives changed order. Methane has a larger impact on climate change on short time horizons and explains this effect. All categories with toxicity has increases with one to two order of magnitudes from the individualist to the egalitarian. The gas alternative is rated as the best option across all toxicity impact categories. The egalitarian rates the electrical ferry as the worst alternative in all four toxicity categories. From the individualist perspective the conventional ferry are the worst in all toxicity categories but freshwater ecotoxicity. For comprehensive background material on this see Appendix E – Vector of Total Impacts Egalitarian and Individualist.

Difference in Number of Trips per Lifetime

Different number of trips for the electrical ferry and the other light weight options were investigated by increasing the number of trips and checking the difference in D_{tot}. The improvements for the electrical ferry carrying out more trips per lifetime compared to the electrical ferry with fewer trips gave improvements between 1 and 17%. Metal depletion were the only impact category where the number of trips had an impact on the result, where the electrical ferry carrying out more trips got less impact than the conventional ferry. The difference between these two alternatives in this category is small, around 3%.

Battery Life

Battery life were varied between eight and 12 years and the ranking of the different ferry alternatives were not affected in any impact categories. The batteries have more than 50% of the total impacts for the all-electric ferry in marine eutrophication. For marine eutrophication the electrical ferry is better than the fossil alternatives independent on the battery life as shown in Figure 34.

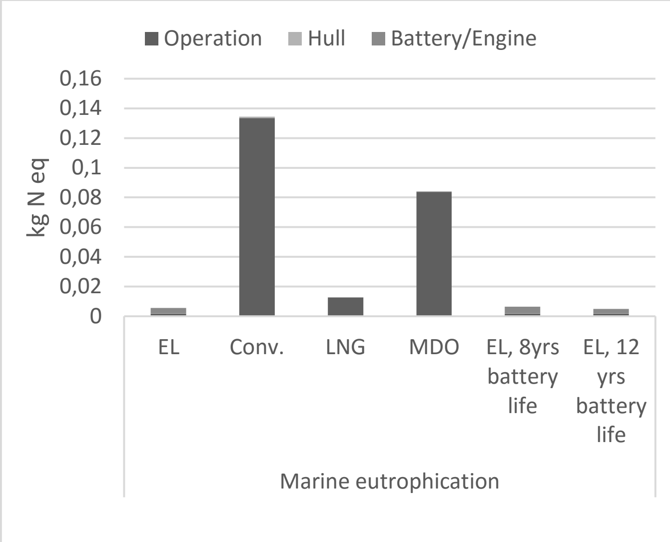


Figure 34: Marine Eutrophication potential for the different ferry options and different battery life.

Electricity Mix

The different electricity mixes used in the analysis were the Norwegian supply mix as baseline alternative, the NORDEL production mix, UCTE production mix and CN supply mix. The difference between supply and production is that supply includes electricity trade between countries and in this sense reflect the physical reality more accurately than the production mixes. The Norwegian supply mix consists of 98% hydropower, making it one of the electricity mixes with the largest proportion of renewable energy. The NORDEL production mix is the production mix of the countries Denmark, Norway, Sweden and Finland. The UCTE (Union for the Coordination of the Transmission of Electricity) consists of many countries in the continental Europe, and their electricity sources are presented in Table 17.

Table 17: Production technology divided on production and supply mix for the different UCTE countries(Dones et al.).

		Domestic production technologies						Imports	Total
		fossil	nuclear	hydro	pumped storage	new renewable	waste		
Austria	production	20.2		77.1	2.6	0.1			100.0
	supply	14.8		56.6	1.9	0.1		26.6	100.0
Belgium	production	38.8	57.6	0.6	1.6	0.3	1.1		100.0
	supply	33.8	50.2	0.5	1.4	0.3	1.0	12.8	100.0
Bosnia Herzegovina	production	51.5		48.5					100.0
	supply	46.7		44.0				9.3	100.0
Croatia	production	41.2		55.1	3.6				100.0
	supply	23.8		31.8	2.1			42.3	100.0
France	production	9.0	76.6	12.8	0.9	0.4	0.4		100.0
	supply	8.9	75.9	12.7	0.9	0.4	0.4	0.9	100.0
Germany	production	62.2	30.4	4.3	0.5	2.0	0.5		100.0
	supply	56.8	27.7	3.9	0.5	1.8	0.5	8.7	100.0
Greece	production	90.7		7.3	0.8	0.9	0.3		100.0
	supply	87.7		7.0	0.8	0.9	0.3	3.3	100.0
Luxemburg	production	18.7		10.4	64.1	2.7	4.2		100.0
	supply	2.8		1.6	9.7	0.4	0.6	84.8	100.0
Macedonia	production	83.5		16.5					100.0
	supply	78.4		15.5				6.1	100.0
the Netherlands	production	89.5	4.4	0.2		2.0	3.9		100.0
	supply	70.2	3.5	0.1		1.6	3.1	21.6	100.0
Portugal	production	67.9		27.1	0.9	2.9	1.2		100.0
	supply	61.1		24.4	0.8	2.6	1.0	10.0	100.0
Serbia and Montenegro	production	65.1		33.4	1.5				100.0
	supply	60.5		31.1	1.4			7.1	100.0
Slovenia	production	34.5	35.6	29.5		0.2	0.3		100.0
	supply	23.9	24.7	20.5		0.1	0.2	30.6	100.0
Switzerland	production	1.6	37.5	56.9	1.3	0.0	2.6		100.0
	supply	1.0	23.4	35.6	0.8	0.0	1.6	37.5	100.0

The CN supply mix is the supply mix of China, and it is included in this analysis a worst case scenario. The Chinese electricity mix consists per 2005 of 79% coal (Frischknecht, Tuchschmid, Faist-Emmenegger, Bauer, & Dones, 2007). 1 kWh of electricity for the different electricity mixes were run and the GWP is reported in Table 18.

Table 18: GWP for the different electricity mixes.

Electricity mix	g CO2 /kWh
Norwegian supply mix	44
NORDEL	163
UCTE	594
CN	1500

Figure 35 shows the GWP for the ferry options and the electrical ferry run on different electricity mixes.

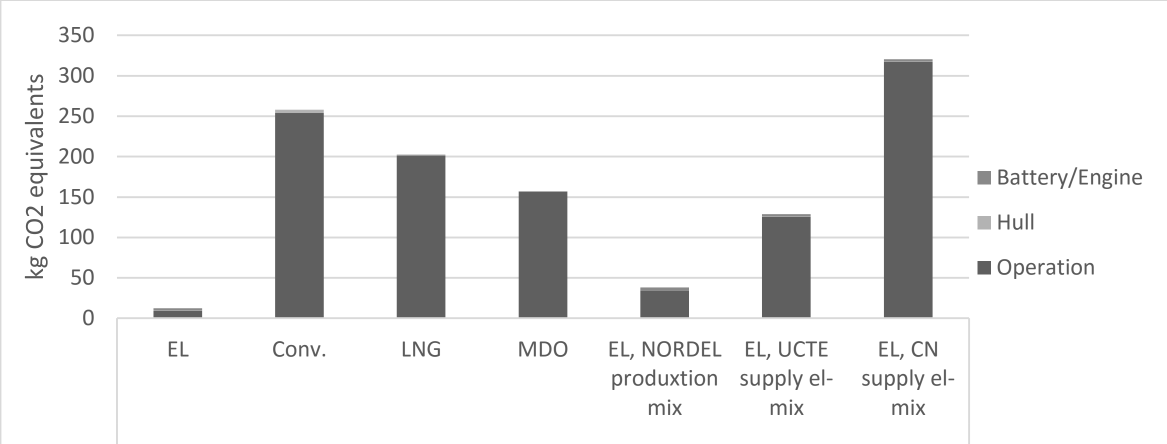


Figure 35: GWP for the ferry options and the all-electric ferry run on different electricity mixes.

Figure 35 shows that the Norwegian electricity mix has significantly less GWP than the other electricity mixes, and that using an electricity mix such as the UCTE is only 22% better than the light weight design run on MDO, while the Chinese electricity mix is 24 % worse than the conventional ferry design run on MDO.

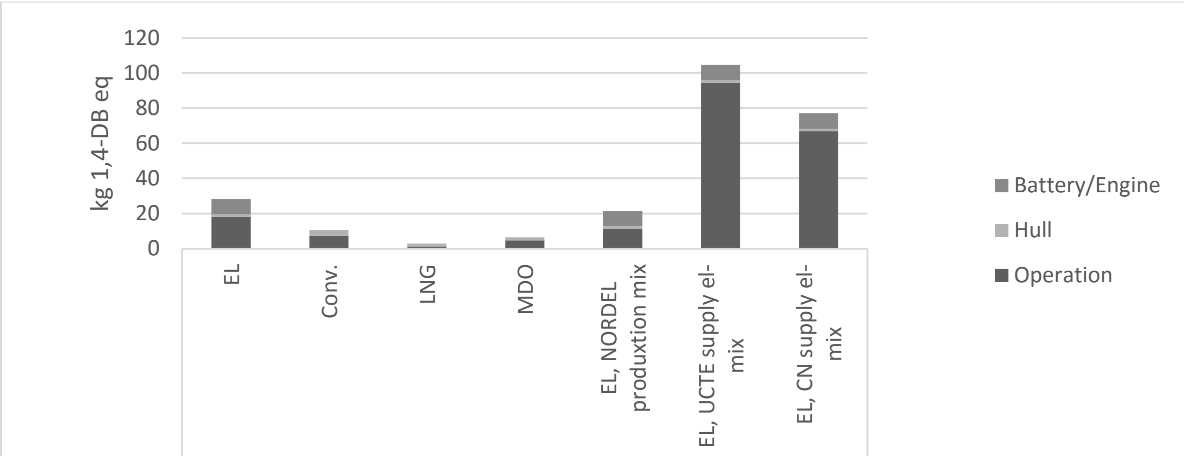
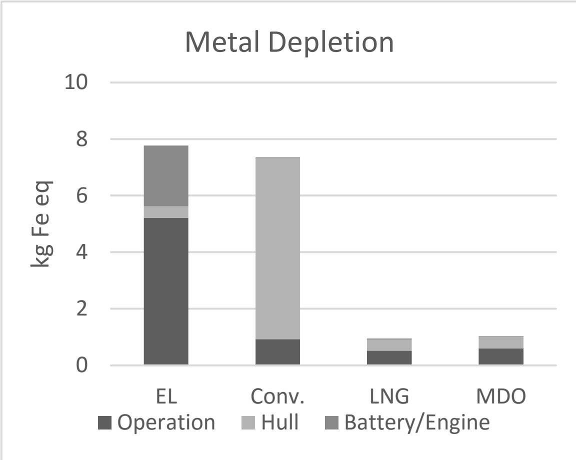


Figure 36: Human toxicity for the ferry options and the all-electric ferry run on different electricity mixes.

Figure 36 shows the human toxicity potential for all ferry options and different electricity mixes. The electrical ferry has the largest human toxicity potential independent on the electricity mix and the UCTE and Chinese electricity mix has substantially larger impacts than all other options.

Modelling of Steel and Aluminium

The modelling of the input material is inconsistent, using secondary aluminium and pig iron for the steel with a secondary material percentage of 35. In order to check how sensitive conclusions were to this modelling error the model were run without aluminium and steel for hull and engines. The omission of hull and engines gave no changes in the internal ranking of the different ferry options in any impact category. In metal depletion a significant reduction were observed for the conventional ferry due to the large contribution of the hull in this category as illustrated in Figure 38 and Figure 37.



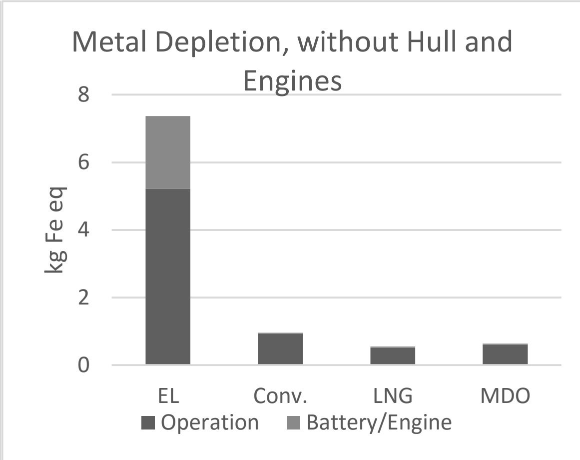


Figure 38: Metal depletion for the four options with hull and engines.

Figure 37: Metal depletion for the four options excluding hull and engines.

7.4 Feasibility of the Ferry Alternatives

The cases where MS Ampere is run on diesel or gas is theoretical cases not tested in reality. Whether these solutions are feasible are complex to determine, and the most important constraints on ships are weight and volume. A ferry is typically a volume critical ship as the demand of accommodating the volume of the load is more difficult to satisfy than the weight. MS Ampere is also a catamaran which is typically weight critical. Therefore estimates on weight and volume implications of the different alternatives should be investigated and this chapter describes a simplified evaluation of this.

The battery pack fitted on MS Ampere has a mass of approximately 10 ton. Engines to be installed on the diesel and gas versions has total masses around 4,5 ton, but the fuel and other engine systems should be taken into account. If fuelling is every 4 day, around 5,5 tonne diesel is required for the diesel version and 14 m^3 LNG for the gas version. The diesel system weight is therefore around 10 tonne fuel and engine included, and assumed to have a similar weight as the battery solution. The LNG solution is more complicated as the fuel needs to be pressurized. An LNG tank accommodating around 14 m^3 LNG has a mass of 7,5 tonne (LNG Global, 2015). This is not including the weight of fuel which is approximately 6 ton. The LNG alternative will therefore have a total weight of 18 ton, which is 8 tonne more than the battery.

The change in trim on MS Ampere were therefore estimated with a weight increase of 10 t to give a conservative estimate. It was assumed that the weight was put evenly giving uniform trim. The waterline area at the design waterline was estimated by measurements on the general arrangement drawing to approximately 38 m^2. A weight of 10 tonne displaces 9,75 m^3 in saltwater, and dividing the volume by the area gives a trim of around 30 cm.

Volume below deck available to accommodate engines and tanks were also estimated by measuring on the general arrangement drawing of MS Ampere. There are currently several void spaces in this area, and the volume were estimated to approximately 130 m^3. A LNG tank with the attributes described earlier can be fitted to the size of a 20 ft container, which has a volume of 35 m^3. The engine itself has a volume of 4 m^2. It should however be noted that the small width of the tank top can give challenges regarding the shape of the tank an engine in addition to accessibility requirements for maintenance.

It was considered realistic that a similar design to MS Ampere can be fitted with either diesel or LNG propulsion, although an LNG version will demand some design changes. The fundamental differences are the fitting of a funnel for air intake and exhaust, as well as class safety regulations regarding safety on a gas fuelled ferry.

8 Conclusion

A simplified comparative LCA of conventional and all-electric car ferries has been carried out. The environmental benefits and burdens associated with an all-electric ferry have been compared to ferries run on fossil fuels. A transparent inventory with explanations is provided for future studies.

To set the thesis in perspective and to give insights to the technologies investigated, a literature review on car ferry developments and current energy efficiency and environmental measures were performed. Lavik-Oppedal was chosen as a basis for the study as the world's first all-electric car ferry MS Ampere operates this route. Therefore some observed data, such as the energy required per trip, could be used. The mathematical modelling of LCA is described and provides theoretical understanding of the method applied in the present study.

LCA using ReCiPe mid-point indicators provides insight to a range of environmental effects of the different ferry options. It also provides insight to the types of processes that contribute to the environmental impacts. Mid-point indictors does not provide a streamlined result of what ferry option is the most environmentally friendly in total. The results might therefore be presented out of context giving an incomplete picture of the analysis and favouring one ferry alternative over the others in one or more impact categories.

A holistic set of results is provided and it demonstrates a similar trend as for all-electrical cars. This consists of a reduction in impacts associated with usage of fossil fuels and increase in toxicity for the all-electric option. Copper inputs to the electricity distribution are the main contributor to the increase in toxicity. A principal difference between MDO and LNG were impacts dependant on sulphur content in the fuel. LNG had less impacts in terrestrial acidification, photochemical oxidant formation and particulate matter formation. In addition LNG has the lowest impacts of all ferry options in all impact categories concerning toxicity.

For the majority of impact categories and ferry options the operation phase has the largest impacts and background processes have large influence on the results. Most background processes are taken from the Ecoinvent 2,2 database, and the choice of processes is therefore considered a source of inaccuracy.

A sensitivity analysis run on the different viewpoints, number of trips per lifetime, battery life, electricity mix used and modelling of metal inputs to hull and engines was carried out. It provided insight to the fact that the results were sensitive to the electricity mix used. The metal inputs for hull and engines increases the impact of the conventional ferry in few impact categories and has large impact only in metal depletion, indicating that the simplification for hull and engines material has limited impact.

A simple evaluation of the feasibility of the two theoretical cases found it possible that a similar design as MS Ampere could be run on MDO or LNG.

Policymakers and companies within the ferry market can use this study to obtain more insight in environmental concerns all-electric ferries and fossil fuel driven alternatives pose. Optimizing regulations for one impact category can have unexpected or undocumented consequences if not investigated. The present study also show that reducing global concerns of climate change associated to ferries can lead to local issues with toxicity.

9 Further Work

There are several actions that could be taken to improve the quality of the present study. Access to full Ecoinvent process descriptions should be obtained to make sure the processes have the intended functions. Insights to the modelling of the database processes can also give additional understanding of the end results. Modelling of recycling should be improved to provide similar recycling percentage for all materials where recycling is relevant.

Other fuels such as hydrogen, when confirmed viable for ferry operation, should be included in the analysis to increase the usefulness of the results. Different ferry designs should also be included in an analysis to investigate all possible options. Processes related to shipbuilding, end of life for batteries and ferry should also be included to obtain more precise results.

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Appendix A – Input File Arda Gui

A_{ff}-Matrix (71x71)

In this Sheet, you enter your foreground data: The process labels (green), the final demand vector (y_f, pink), and your foreground requirement matrix

	Label (PRO_f): FULL NAME	PROCES	Name	Other ID	Infrastruc	Locatior	Categor	Subcateg	UNIT	y_f:	A_ff: 1 Op. EL	2 Op. COI	3 Op. Gas_	4 Op. Diese	5 Pro. E	6 Pro. CON	7 Pro. Gas
1	Op. EL	10001	Operation EL							0							
2	Op. CONV	10002	Operation CONV							0							
3	Op. Gas_Ampere	10003	Operation gas							1							
4	Op. Diesel Ampere	10004	Operation diesel							0							
5	Pro. EL	10005	Production EL							0	2,77E-06						
6	Pro. CONV	10006	Production CONV							0		2E-06					
7	Pro. Gas_Ampere	10007											2,8E-06				
8	Pro. Diesel Ampere	10008												2,8E-06			
9	EOL EL	10009									2,8E-06						
10	EOL CONV	10010										2E-06					
11	EOL Gas_Ampere	10011											2,8E-06				
12	EOL Diesel Ampere	10012												2,8E-06			
13	Hull El	10013													1		1
14	Hull CONV	10014														1	
15	Battery	10015									5,5E-06				1		
16	Engine conv, large	10016														1	
17	engine small	10017															1
18	Battery EOL	10018															
19	Engine large EOL	10019															
20	Engine small EOL	10020															
21	**Marine battery**	10021															
22	Battery packaging	10022															
23	BMS	10023															
24	Cooling system	10024															
25	Battery cell	10025															
26	Battery tray	10026															
27	Battery retention	10027															
28	Tray w fixings	10028															
29	Tray lid	10029															
30	Tray seal	10030															
31	Strap retention	10031															
32	Lower retention	10032															
33	Heat transfer plates	10033															
34	Low Voltage system	10034															
35	High Voltage system	10035															
36	IBIS fixings	10036															
37	IBIS	10037															
38	Radiator	10038															
39	Manifolds	10039															
40	Clamps & fixings	10040															
41	Pipe fitting	10041															
42	Thermal pad	10042															
43	Module packaging	10043															
44	Module fixings	10044															
45	Outer frame	10045															
46	Inner frame	10046															
47	Bimetallic busbars	10047															
48	Endbusbar, Al	10048															
49	Endbusbar, Cu	10049															
50	Aluminium "box"	10050															
51	Electrolyte	10051															
52	Cathode	10052															
53	Anode	10053															
54	Cell container	10054															
55	Separator	10055															
56	Positive current collecto	10056															
57	Positive electrode paste	10057															
58	Negative current collect	10058															
59	Negative electrode past	10059															
60	Tab, aluminum	10060															
61	Tab, copper	10061															
62	Aluminum pouch	10062															
63	Li[Ni(1/3)Co(1/3)Mn(1/3	10063															
64	Ni(1/3)Co(1/3)Mn(1/3)	10064															
65	Nickel Sulphate	10065															
66	Cobalt Sulphate	10066															
67	Manganese Sulphate	10067															
68	Lithium hexafluorophos	10068															
69	LiF	10069															
70	PCl5	10070															
71	Lithium carbonate	10071															

In this Sheet, you enter your f((A_ff, orange)

	Label (PRO_f):		8	9	10	11	12	13	14	15	16	17	18	19	20	21
	FULL NAME	PROCES:	Pro. Dies	EOL EL	EOL COI	EOL Gas	EOL Die:	Hull El	Hull CON	Battery	Engine c	engine s	Battery E	Engine l	Engine s	Marine b
1	Op. EL	10001														
2	Op. CONV	10002														
3	Op. Gas_Ampere	10003														
4	Op. Diesel Ampere	10004														
5	Pro. EL	10005														
6	Pro. CONV	10006														
7	Pro. Gas_Ampere	10007														
8	Pro. Diesel Ampere	10008														
9	EOL EL	10009														
10	EOL CONV	10010														
11	EOL Gas_Ampere	10011														
12	EOL Diesel Ampere	10012														
13	Hull El	10013	1													
14	Hull CONV	10014														
15	Battery	10015														
16	Engine conv. large	10016														
17	engine small	10017	1													
18	Battery EOL	10018		3												
19	Engine large EOL	10019			1											
20	Engine small EOL	10020				1	1									
21	**Marine battery**	10021								20206						
22	Battery packaging	10022														0,4228
23	BMS	10023														0,0326
24	Cooling system	10024														0,0175
25	Battery cell	10025														0,5271
26	Battery tray	10026														
27	Battery retention	10027														
28	Tray w fixings	10028														
29	Tray lid	10029														
30	Tray seal	10030														
31	Strap retention	10031														
32	Lower retention	10032														
33	Heat transfer plates	10033														
34	Low Voltage system	10034														
35	High Voltage system	10035														
36	IBIS fixings	10036														
37	IBIS	10037														
38	Radiator	10038														
39	Manifolds	10039														
40	Clamps & fixings	10040														
41	Pipe fitting	10041														
42	Thermal pad	10042														
43	Module packaging	10043														
44	Module fixings	10044														
45	Outer frame	10045														
46	Inner frame	10046														
47	Bimetallic busbars	10047														
48	Endbusbar, Al	10048														
49	Endbusbar, Cu	10049														
50	Aluminium "box"	10050														
51	Electrolyte	10051														
52	Cathode	10052														
53	Anode	10053														
54	Cell container	10054														
55	Separator	10055														
56	Positive current collecto	10056														
57	Positive electrode paste	10057														
58	Negative current collect	10058														
59	Negative electrode past	10059														
60	Tab, aluminum	10060														
61	Tab, copper	10061														
62	Aluminum pouch	10062														
63	Li[Ni(1/3)Co(1/3)Mn(1/3	10063														
64	Ni(1/3)Co(1/3)Mn(1/3)	10064														
65	Nickel Sulphate	10065														
66	Cobalt Sulphate	10066														
67	Manganese Sulphate	10067														
68	Lithium hexafluorophos	10068														
69	LiF	10069														
70	PCl5	10070														
71	Lithium carbonate	10071														

In this Sheet, you enter your f																		
	Label (PRO_f):		22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
	FULL NAME	PROCES	Battery p	BMS	Cooling s	Battery c	Battery tr	Battery r	Tray w fi	Tray lid	Tray seal	Strap ret	Lower re	Heat tran	Low Volt	High Volt	IBIS fixin	IBIS
1	Op. EL	10001																
2	Op. CONV	10002																
3	Op. Gas_Ampere	10003																
4	Op. Diesel Ampere	10004																
5	Pro. EL	10005																
6	Pro. CONV	10006																
7	Pro. Gas_Ampere	10007																
8	Pro. Diesel Ampere	10008																
9	EOL EL	10009																
10	EOL CONV	10010																
11	EOL Gas_Ampere	10011																
12	EOL Diesel Ampere	10012																
13	Hull El	10013																
14	Hull CONV	10014																
15	Battery	10015																
16	Engine conv, large	10016																
17	engine small	10017																
18	Battery EOL	10018																
19	Engine large EOL	10019																
20	Engine small EOL	10020																
21	**Marine battery**	10021																
22	Battery packaging	10022																
23	BMS	10023																
24	Cooling system	10024																
25	Battery cell	10025																
26	Battery tray	10026	0,2531															
27	Battery retention	10027	0															
28	Tray w fixings	10028					0,7916											
29	Tray lid	10029					0,208											
30	Tray seal	10030					0,0004											
31	Strap retention	10031						0,0872										
32	Lower retention	10032						0,3495										
33	Heat transfer plates	10033						0,4612										
34	Low Voltage system	10034		0,0019														
35	High Voltage system	10035		0,0043														
36	IBIS fixings	10036		4E-05														
37	IBIS	10037		0,0068														
38	Radiator	10038			0,0257													
39	Manifolds	10039			0,0011													
40	Clamps & fixings	10040			0,0007													
41	Pipe fitting	10041			3E-05													
42	Thermal pad	10042			0,0006													
43	Module packaging	10043	0,7469															
44	Module fixings	10044																
45	Outer frame	10045																
46	Inner frame	10046																
47	Bimetallic busbars	10047																
48	Endbusbar, Al	10048																
49	Endbusbar, Cu	10049																
50	Aluminium "box"	10050																
51	Electrolyte	10051				0,1575												
52	Cathode	10052				0,4284												
53	Anode	10053				0,3855												
54	Cell container	10054				0,0067												
55	Separator	10055				0,0219												
56	Positive current collecto	10056																
57	Positive electrode paste	10057																
58	Negative current collect	10058																
59	Negative electrode past	10059																
60	Tab, aluminum	10060																
61	Tab, copper	10061																
62	Aluminum pouch	10062																
63	Li[Ni(1/3)Co(1/3)Mn(1/3	10063																
64	Ni(1/3)Co(1/3)Mn(1/3)	10064																
65	Nickel Sulphate	10065																
66	Cobalt Sulphate	10066																
67	Manganese Sulphate	10067																
68	Lithium hexafluorophos	10068																
69	LiF	10069																
70	PCl5	10070																
71	Lithium carbonate	10071																

In this Sheet, you enter your f

	Label (PRO_f):		38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
	FULL NAME	PROCES	Radiator	Manifold	Clamps &	Pipe fittir	Thermal	Module p	Module f	Outer fra	Inner fra	Bimetalli	Endbusb	Endbusb	Aluminiu	Electroly	Cathode	Anode
1	Op. EL	10001																
2	Op. CONV	10002																
3	Op. Gas_Ampere	10003																
4	Op. Diesel Ampere	10004																
5	Pro. EL	10005																
6	Pro. CONV	10006																
7	Pro. Gas_Ampere	10007																
8	Pro. Diesel Ampere	10008																
9	EOL EL	10009																
10	EOL CONV	10010																
11	EOL Gas_Ampere	10011																
12	EOL Diesel Ampere	10012																
13	Hull El	10013																
14	Hull CONV	10014																
15	Battery	10015																
16	Engine conv, large	10016																
17	engine small	10017																
18	Battery EOL	10018																
19	Engine large EOL	10019																
20	Engine small EOL	10020																
21	**Marine battery**	10021																
22	Battery packaging	10022																
23	BMS	10023																
24	Cooling system	10024																
25	Battery cell	10025																
26	Battery tray	10026																
27	Battery retention	10027																
28	Tray w fixings	10028																
29	Tray lid	10029																
30	Tray seal	10030																
31	Strap retention	10031																
32	Lower retention	10032																
33	Heat transfer plates	10033																
34	Low Voltage system	10034																
35	High Voltage system	10035																
36	IBIS fixings	10036																
37	IBIS	10037																
38	Radiator	10038																
39	Manifolds	10039																
40	Clamps & fixings	10040																
41	Pipe fitting	10041																
42	Thermal pad	10042																
43	Module packaging	10043																
44	Module fixings	10044						0										
45	Outer frame	10045						0,2525										
46	Inner frame	10046						0,213										
47	Bimetallic busbars	10047						0,0181										
48	Endbusbar, Al	10048						0,0009										
49	Endbusbar, Cu	10049						0,0026										
50	Aluminium "box"	10050						0,5129										
51	Electrolyte	10051																
52	Cathode	10052																
53	Anode	10053																
54	Cell container	10054																
55	Separator	10055																
56	Positive current collecto	10056															0,1145	
57	Positive electrode paste	10057															0,8855	
58	Negative current collect	10058																0,5737
59	Negative electrode past	10059																0,4263
60	Tab, aluminum	10060																
61	Tab, copper	10061																0,3778
62	Aluminum pouch	10062																0,4029
63	Li[Ni(1/3)Co(1/3)Mn(1/3	10063																
64	Ni(1/3)Co(1/3)Mn(1/3)	10064																
65	Nickel Sulphate	10065																
66	Cobalt Sulphate	10066																
67	Manganese Sulphate	10067																
68	Lithium hexafluorophos	10068												0,1162				
69	LiF	10069																
70	PCl5	10070																
71	Lithium carbonate	10071																

In this Sheet, you enter your f

	Label (PRO_f):		54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	FULL NAME	PROCES	Cell cont	Separato	Positive	Positive	Negative	Negative	Tab, alun	Tab, cop	Aluminur	Li[Ni(1/3)	Ni(1/3)Co	Nickel S	Cobalt S	Mangane	Lithium h	LiF	PCl5	Lithium c
1	Op. EL	10001																		
2	Op. CONV	10002																		
3	Op. Gas_Ampere	10003																		
4	Op. Diesel Ampere	10004																		
5	Pro. EL	10005																		
6	Pro. CONV	10006																		
7	Pro. Gas_Ampere	10007																		
8	Pro. Diesel Ampere	10008																		
9	EOL EL	10009																		
10	EOL CONV	10010																		
11	EOL Gas_Ampere	10011																		
12	EOL Diesel Ampere	10012																		
13	Hull El	10013																		
14	Hull CONV	10014																		
15	Battery	10015																		
16	Engine conv, large	10016																		
17	engine small	10017																		
18	Battery EOL	10018																		
19	Engine large EOL	10019																		
20	Engine small EOL	10020																		
21	**Marine battery**	10021																		
22	Battery packaging	10022																		
23	BMS	10023																		
24	Cooling system	10024																		
25	Battery cell	10025																		
26	Battery tray	10026																		
27	Battery retention	10027																		
28	Tray w fixings	10028																		
29	Tray lid	10029																		
30	Tray seal	10030																		
31	Strap retention	10031																		
32	Lower retention	10032																		
33	Heat transfer plates	10033																		
34	Low Voltage system	10034																		
35	High Voltage system	10035																		
36	IBIS fixings	10036																		
37	IBIS	10037																		
38	Radiator	10038																		
39	Manifolds	10039																		
40	Clamps & fixings	10040																		
41	Pipe fitting	10041																		
42	Thermal pad	10042																		
43	Module packaging	10043																		
44	Module fixings	10044																		
45	Outer frame	10045																		
46	Inner frame	10046																		
47	Bimetallic busbars	10047																		
48	Endbusbar, Al	10048																		
49	Endbusbar, Cu	10049																		
50	Aluminium "box"	10050																		
51	Electrolyte	10051																		
52	Cathode	10052																		
53	Anode	10053																		
54	Cell container	10054																		
55	Separator	10055																		
56	Positive current collecto	10056																		
57	Positive electrode paste	10057																		
58	Negative current collect	10058																		
59	Negative electrode past	10059																		
60	Tab, aluminum	10060	0,2193																	
61	Tab, copper	10061	0,3778																	
62	Aluminum pouch	10062	0,4029																	
63	Li[Ni(1/3)Co(1/3)Mn(1/3	10063				0,94														
64	Ni(1/3)Co(1/3)Mn(1/3)	10064										0,9486								
65	Nickel Sulphate	10065											0,5654							
66	Cobalt Sulphate	10066											0,5663							
67	Manganese Sulphate	10067											0,5517							
68	Lithium hexafluorophos	10068																		
69	LiF	10069															0,197			
70	PCl5	10070															1,98			
71	Lithium carbonate	10071																1,49		

A_{bf} inputs

1	*In this sheet, you enter the coordinates of the requirements placed on the background by the*					
2	*foreground. This will be assembled as an A_bf matrix*					
3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
5	electricity, low voltage, production NO, at grid/ NO/ kWh	Op. EL	**960**	10001	2,12E+02	kWh
6	diesel, low-sulphur, at regional storage/ CH/ kg	Op. CONV	**2347**	10002	6,57E+01	kg
7	natural gas, high pressure, at consumer/ RER/ MJ	Op. Gas_Ampere	**2089**	10003	2,46E+03	MJ
8	diesel, low-sulphur, at regional storage/ CH/ kg	Op. Diesel_Ampere	**2347**	10004	4,04E+01	kg
9	electricity, medium voltage, at grid/ NO/ kWh	Marine battery	**1159**	10021	5,02E-06	kWh
10	facilities precious metal refinery/ SE/ unit	Marine battery	**3724**	10021	1,88E-08	p
11	transport, lorry >16t, fleet average/ RER/ tkm	Marine battery	**2807**	10021	1,38E-01	tkm
12	transport, transoceanic freight ship/ OCE/ tkm	Marine battery	**2853**	10021	4,29E+00	tkm
13	transport, lorry >16t, fleet average/ RER/ tkm	Battery packaging	**2807**	10022	1,95E-01	tkm
14	transport, transoceanic freight ship/ OCE/ tkm	Battery packaging	**2853**	10022	6,08E+00	tkm
15	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg	BMS	**1289**	10023	1,28E-03	kg
16	transport, freight, rail/ RER/ tkm	BMS	**2887**	10023	2,86E-03	tkm
17	transport, lorry >32t, EURO3/ RER/ tkm	BMS	**2809**	10023	1,43E-03	tkm
18	ethylene glycol, at plant/ RER/ kg	Cooling system	**706**	10024	1,41E-03	kg
19	transport, freight, rail/ RER/ tkm	Cooling system	**2887**	10024	6,48E-03	tkm
20	transport, lorry >32t, EURO3/ RER/ tkm	Cooling system	**2809**	10024	2,96E-03	tkm
21	water, decarbonised, at plant/ RER/ kg	Battery cell	**3389**	10025	3,80E+02	kg
22	electricity, peat, at power plant/ NORDEL/ kWh	Battery cell	**1593**	10025	0,00E+00	kWh
23	electricity, hard coal, at power plant/ UCTE/ kWh	Battery cell	**1406**	10025	1,33E+01	kWh
24	electricity, oil, at power plant/ UCTE/ kWh	Battery cell	**2432**	10025	1,26E+00	kWh
25	electricity, natural gas, at power plant/ UCTE/ kWh	Battery cell	**2144**	10025	4,49E+00	kWh
26	electricity from waste, at municipal waste incineration plant/ CH/ kWh	Battery cell	**3152**	10025	1,28E-02	kWh
27	electricity, nuclear, at power plant/ UCTE/ kWh	Battery cell	**2251**	10025	9,43E+00	kWh
28	electricity, hydropower, at power plant/ CH/ kWh	Battery cell	**1492**	10025	3,93E-01	kWh
29	electricity, production mix photovoltaic, at plant/ US/ kWh	Battery cell	**2601**	10025	3,61E-02	kWh
30	electricity, at wind power plant/ RER/ kWh	Battery cell	**3392**	10025	4,37E-02	kWh
31	transmission network, electricity, high voltage/ CH/ km	Battery cell	**3666**	10025	2,45E-07	km

1 *In this sheet, you enter the coordinates of the requirements placed on the background by the*
2 *foreground. This will be assembled as an A_bf matrix*

3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
32	transmission network, long-distance/ UCTE/ km	Battery cell	**3668**	10025	9,20E-09	km
33	transmission network, electricity, medium voltage/ CH/ km	Battery cell	**3667**	10025	9,21E-07	km
34	sulphur hexafluoride, liquid, at plant/ RER/ kg	Battery cell	**600**	10025	2,14E-06	kg
35	facilities precious metal refinery/ SE/ unit	Battery cell	**3724**	10025	1,88E-08	p
36	transport, freight, rail/ RER/ tkm	Battery cell	**2887**	10025	2,63E-01	tkm
37	transport, lorry >32t, EURO3/ RER/ tkm	Battery cell	**2809**	10025	1,00E-01	tkm
38	transport, freight, rail/ RER/ tkm	Battery tray	**2887**	10026	2,00E-01	tkm
39	transport, lorry >32t, EURO3/ RER/ tkm	Battery tray	**2809**	10026	1,00E-01	tkm
40	synthetic rubber, at plant/ RER/ kg	Battery retention	**2677**	10027	1,02E-01	kg
41	injection moulding/ RER/ kg	Battery retention	**2683**	10027	1,02E-01	kg
42	transport, freight, rail/ RER/ tkm	Battery retention	**2887**	10027	2,00E-01	tkm
43	transport, lorry >32t, EURO3/ RER/ tkm	Battery retention	**2809**	10027	1,00E-01	tkm
44	steel, low-alloyed, at plant/ RER/ kg	Tray w fixings	**1914**	10028	1,00E+00	kg
45	steel product manufacturing, average metal working/ RER/ kg	Tray w fixings	**1939**	10028	1,00E+00	kg
46	transport, freight, rail/ RER/ tkm	Tray w fixings	**2887**	10028	2,00E-01	tkm
47	transport, lorry >32t, EURO3/ RER/ tkm	Tray w fixings	**2809**	10028	1,00E-01	tkm
48	metal working factory/ RER/ unit	Tray w fixings	**3741**	10028	4,58E-10	p
49	polypropylene, granulate, at plant/ RER/ kg	Tray lid	**2662**	10029	1,00E+00	kg
50	injection moulding/ RER/ kg	Tray lid	**2683**	10029	1,00E+00	kg
51	transport, freight, rail/ RER/ tkm	Tray lid	**2887**	10029	2,00E-01	tkm
52	transport, lorry >32t, EURO3/ RER/ tkm	Tray lid	**2809**	10029	1,00E-01	tkm
53	plastics processing factory/ RER/ unit	Tray lid	**4006**	10029	7,41E-10	p
54	butyl acrylate, at plant/ RER/ kg	Tray seal	**668**	10030	1,00E+00	kg
55	injection moulding/ RER/ kg	Tray seal	**2683**	10030	1,00E+00	kg
56	transport, freight, rail/ RER/ tkm	Tray seal	**2887**	10030	2,00E-01	tkm
57	transport, lorry >32t, EURO3/ RER/ tkm	Tray seal	**2809**	10030	1,00E-01	tkm
58	plastics processing factory/ RER/ unit	Tray seal	**4006**	10030	7,41E-10	p
59	nylon 6, at plant/ RER/ kg	Strap retention	**2647**	10031	1,33E-01	kg
60	polypropylene, granulate, at plant/ RER/ kg	Strap retention	**2662**	10031	3,79E-01	kg
61	steel, low-alloyed, at plant/ RER/ kg	Strap retention	**1914**	10031	4,87E-01	kg

1 *In this sheet, you enter the coordinates of the requirements placed on the background by the*
2 *foreground. This will be assembled as an A_bf matrix*

Row	Background Name	Foreground Process Name	(Arda ID)	(Process ID)		Unit
4	*Comment*	*Comment*	BACKGROUND ID	FOREGROUND ID	AMOUNT	*Comment*
62	steel product manufacturing, average metal working/ RER/ kg	Strap retention	1939	10031	4,87E-01	kg
63	injection moulding/ RER/ kg	Strap retention	2683	10031	5,13E-01	kg
64	transport, freight, rail/ RER/ tkm	Strap retention	2887	10031	2,00E-01	tkm
65	transport, lorry >32t, EURO3/ RER/ tkm	Strap retention	2809	10031	1,00E-01	tkm
66	metal working factory/ RER/ unit	Strap retention	3741	10031	2,23E-10	p
67	plastics processing factory/ RER/ unit	Strap retention	4006	10031	3,80E-10	p
68	steel, low-alloyed, at plant/ RER/ kg	Lower retention	1914	10032	1,00E+00	kg
69	steel product manufacturing, average metal working/ RER/ kg	Lower retention	1939	10032	1,00E+00	kg
70	transport, freight, rail/ RER/ tkm	Lower retention	2887	10032	2,00E-01	tkm
71	transport, lorry >32t, EURO3/ RER/ tkm	Lower retention	2809	10032	1,00E-01	tkm
72	metal working factory/ RER/ unit	Lower retention	3741	10032	4,58E-10	p
73	steel, low-alloyed, at plant/ RER/ kg	Heat transfer plates	1914	10033	1,00E+00	kg
74	steel product manufacturing, average metal working/ RER/ kg	Heat transfer plates	1939	10033	1,00E+00	kg
75	transport, freight, rail/ RER/ tkm	Heat transfer plates	2887	10033	2,00E-01	tkm
76	transport, lorry >32t, EURO3/ RER/ tkm	Heat transfer plates	2809	10033	1,00E-01	tkm
77	metal working factory/ RER/ unit	Heat transfer plates	3741	10033	4,58E-10	p
78	nylon 66, at plant/ RER/ kg	Low Voltage system	2649	10034	2,90E-02	kg
79	electronic component, passive, unspecified, at plant/ GLO/ kg	Low Voltage system	1205	10034	9,71E-01	kg
80	injection moulding/ RER/ kg	Low Voltage system	2683	10034	2,90E-02	kg
81	transport, freight, rail/ RER/ tkm	Low Voltage system	2887	10034	2,00E-01	tkm
82	transport, lorry >32t, EURO3/ RER/ tkm	Low Voltage system	2809	10034	1,00E-01	tkm
83	electronic component production plant/ GLO/ unit	Low Voltage system	3670	10034	2,00E-08	p
84	steel, low-alloyed, at plant/ RER/ kg	High Voltage system	1914	10035	1,43E-03	kg
85	aluminium, production mix, at plant/ RER/ kg	High Voltage system	1757	10035	1,22E-01	kg
86	nylon 66, at plant/ RER/ kg	High Voltage system	2649	10035	4,40E-02	kg
87	synthetic rubber, at plant/ RER/ kg	High Voltage system	2677	10035	3,58E-03	kg
88	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg	High Voltage system	2653	10035	5,68E-02	kg
89	copper, primary, at refinery/ GLO/ kg	High Voltage system	1796	10035	2,32E-01	kg
90	copper, secondary, at refinery/ RER/ kg	High Voltage system	1805	10035	4,10E-02	kg
91	polyphenylene sulfide, at plant/ GLO/ kg	High Voltage system	2661	10035	3,22E-02	kg

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4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
92	tin, at regional storage/ RER/ kg	High Voltage system	**1918**	10035	1,61E-02	kg
93	cable, ribbon cable, 20-pin, with plugs, at plant/ GLO/ kg	High Voltage system	**1186**	10035	4,50E-01	kg
94	steel product manufacturing, average metal working/ RER/ kg	High Voltage system	**1939**	10035	1,43E-03	kg
95	aluminium product manufacturing, average metal working/ RER/ kg	High Voltage system	**1924**	10035	1,22E-01	kg
96	injection moulding/ RER/ kg	High Voltage system	**2683**	10035	1,37E-01	kg
97	copper product manufacturing, average metal working/ RER/ kg	High Voltage system	**1926**	10035	2,74E-01	kg
98	metal product manufacturing, average metal working/ RER/ kg	High Voltage system	**1928**	10035	1,61E-02	kg
99	transport, freight, rail/ RER/ tkm	High Voltage system	**2887**	10035	1,10E-01	tkm
100	transport, lorry >32t, EURO3/ RER/ tkm	High Voltage system	**2809**	10035	5,50E-02	tkm
101	electronic component production plant/ GLO/ unit	High Voltage system	**3670**	10035	2,00E-08	p
102	steel, low-alloyed, at plant/ RER/ kg	IBIS fixings	**1914**	10036	1,00E+00	kg
103	steel product manufacturing, average metal working/ RER/ kg	IBIS fixings	**1939**	10036	1,00E+00	kg
104	transport, freight, rail/ RER/ tkm	IBIS fixings	**2887**	10036	2,00E-01	tkm
105	transport, lorry >32t, EURO3/ RER/ tkm	IBIS fixings	**2809**	10036	1,00E-01	tkm
106	metal working factory/ RER/ unit	IBIS fixings	**3741**	10036	4,58E-10	p
107	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	IBIS	**2642**	10037	2,01E-04	kg
108	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg	IBIS	**1289**	10037	1,09E-01	kg
109	integrated circuit, IC, logic type, at plant/ GLO/ kg	IBIS	**1214**	10037	1,69E-05	kg
110	steel, low-alloyed, at plant/ RER/ kg	IBIS	**1914**	10037	8,55E-01	kg
111	connector, clamp connection, at plant/ GLO/ kg	IBIS	**1196**	10037	2,13E-02	kg
112	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg	IBIS	**2653**	10037	6,76E-03	kg
113	nylon 6, at plant/ RER/ kg	IBIS	**2647**	10037	1,89E-03	kg
114	brass, at plant/ CH/ kg	IBIS	**1766**	10037	5,66E-03	kg
115	steel product manufacturing, average metal working/ RER/ kg	IBIS	**1939**	10037	8,55E-01	kg
116	injection moulding/ RER/ kg	IBIS	**2683**	10037	8,85E-03	kg
117	casting, brass/ CH/ kg	IBIS	**1941**	10037	5,66E-03	kg
118	transport, freight, rail/ RER/ tkm	IBIS	**2887**	10037	1,74E-01	tkm
119	transport, lorry >32t, EURO3/ RER/ tkm	IBIS	**2809**	10037	8,69E-02	tkm

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4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
119	transport, lorry >32t, EURO3/ RER/ tkm	IBIS	**2809**	10037	8,69E-02	tkm
120	electronic component production plant/ GLO/ unit	IBIS	**3670**	10037	2,00E-08	p
121	aluminium, production mix, at plant/ RER/ kg	Radiator	**1757**	10038	1,00E+00	kg
122	sheet rolling, aluminium/ RER/ kg	Radiator	**1953**	10038	1,00E+00	kg
123	transport, freight, rail/ RER/ tkm	Radiator	**2887**	10038	2,00E-01	tkm
124	transport, lorry >32t, EURO3/ RER/ tkm	Radiator	**2809**	10038	1,00E-01	tkm
125	aluminium casting, plant/ RER/ unit	Radiator	**3713**	10038	1,54E-10	p
126	aluminium, production mix, at plant/ RER/ kg	Manifolds	**1757**	10039	1,00E+00	kg
127	aluminium product manufacturing, average metal working/ RER/ kg	Manifolds	**1924**	10039	1,00E+00	kg
128	transport, freight, rail/ RER/ tkm	Manifolds	**2887**	10039	2,00E-01	tkm
129	transport, lorry >32t, EURO3/ RER/ tkm	Manifolds	**2809**	10039	1,00E-01	tkm
130	aluminium casting, plant/ RER/ unit	Manifolds	**3713**	10039	1,54E-10	p
131	steel, low-alloyed, at plant/ RER/ kg	Clamps & fixings	**1914**	10040	1,00E+00	kg
132	steel product manufacturing, average metal working/ RER/ kg	Clamps & fixings	**1939**	10040	1,00E+00	kg
133	transport, freight, rail/ RER/ tkm	Clamps & fixings	**2887**	10040	2,00E-01	tkm
134	transport, lorry >32t, EURO3/ RER/ tkm	Clamps & fixings	**2809**	10040	1,00E-01	tkm
135	metal working factory/ RER/ unit	Clamps & fixings	**3741**	10040	4,58E-10	p
136	polyvinylchloride, at regional storage/ RER/ kg	Pipe fitting	**2669**	10041	7,50E-01	kg
137	synthetic rubber, at plant/ RER/ kg	Pipe fitting	**2676**	10041	2,50E-01	kg
138	injection moulding/ RER/ kg	Pipe fitting	**2683**	10041	1,00E+00	kg
139	transport, freight, rail/ RER/ tkm	Pipe fitting	**2887**	10041	2,00E-01	tkm
140	transport, lorry >32t, EURO3/ RER/ tkm	Pipe fitting	**2809**	10041	1,00E-01	tkm
141	plastics processing factory/ RER/ unit	Pipe fitting	**4006**	10041	7,41E-10	p
142	glass fibre, at plant/ RER/ kg	Thermal pad	**1358**	10042	1,00E-01	kg
143	silicon, electronic grade, at plant/ DE/ kg	Thermal pad	**1972**	10042	3,00E-01	kg
144	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	Thermal pad	**2642**	10042	6,00E-01	kg
145	injection moulding/ RER/ kg	Thermal pad	**2683**	10042	1,00E+00	kg
146	transport, freight, rail/ RER/ tkm	Thermal pad	**2887**	10042	2,00E-01	tkm
147	transport, lorry >32t, EURO3/ RER/ tkm	Thermal pad	**2809**	10042	1,00E-01	tkm
148	plastics processing factory/ RER/ unit	Thermal pad	**4006**	10042	7,41E-10	p

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149	transport, freight, rail/ RER/ tkm	Module packaging	**2887**	10043	2,00E-01	tkm
150	transport, lorry >32t, EURO3/ RER/ tkm	Module packaging	**2809**	10043	1,00E-01	tkm
151	facilities precious metal refinery/ SE/ unit	Battery packaging	**3724**	10022	1,88E-08	p
152	steel, low-alloyed, at plant/ RER/ kg	Module fixings	**1914**	10044	0,00E+00	kg
153	nylon 6, at plant/ RER/ kg	Module fixings	**2647**	10044	0,00E+00	kg
154	steel product manufacturing, average metal working/ RER/ kg	Module fixings	**1939**	10044	0,00E+00	kg
155	injection moulding/ RER/ kg	Module fixings	**2683**	10044	0,00E+00	kg
156	transport, freight, rail/ RER/ tkm	Module fixings	**2887**	10044	0,00E+00	tkm
157	transport, lorry >32t, EURO3/ RER/ tkm	Module fixings	**2809**	10044	0,00E+00	tkm
158	metal working factory/ RER/ unit	Module fixings	**3741**	10044	0,00E+00	p
159	plastics processing factory/ RER/ unit	Module fixings	**4006**	10044	0,00E+00	p
160	nylon 66, glass-filled, at plant/ RER/ kg	Outer frame	**2650**	10045	2,97E-01	kg
161	aluminium, production mix, at plant/ RER/ kg	Outer frame	**1757**	10045	7,03E-01	kg
162	injection moulding/ RER/ kg	Outer frame	**2683**	10045	2,97E-01	kg
163	anodising, aluminium sheet/ RER/ m2	Outer frame	**1940**	10045	3,00E-02	m2
164	sheet rolling, aluminium/ RER/ kg	Outer frame	**1953**	10045	7,03E-01	kg
165	transport, freight, rail/ RER/ tkm	Outer frame	**2887**	10045	2,00E-01	tkm
166	transport, lorry >32t, EURO3/ RER/ tkm	Outer frame	**2809**	10045	1,00E-01	tkm
167	plastics processing factory/ RER/ unit	Outer frame	**4006**	10045	2,20E-10	p
168	aluminium casting, plant/ RER/ unit	Outer frame	**3713**	10045	1,08E-10	p
169	nylon 66, glass-filled, at plant/ RER/ kg	Inner frame	**2650**	10046	3,52E-01	kg
170	aluminium, production mix, at plant/ RER/ kg	Inner frame	**1757**	10046	6,48E-01	kg
171	anodising, aluminium sheet/ RER/ m2	Inner frame	**1940**	10046	3,00E-02	m2
172	injection moulding/ RER/ kg	Inner frame	**2683**	10046	3,52E-01	kg
173	sheet rolling, aluminium/ RER/ kg	Inner frame	**1953**	10046	6,48E-01	kg
174	transport, freight, rail/ RER/ tkm	Inner frame	**2887**	10046	2,00E-01	tkm
175	transport, lorry >32t, EURO3/ RER/ tkm	Inner frame	**2809**	10046	1,00E-01	tkm
176	plastics processing factory/ RER/ unit	Inner frame	**4006**	10046	2,61E-10	p
177	aluminium casting, plant/ RER/ unit	Inner frame	**3713**	10046	9,97E-11	p
178	aluminium, production mix, at plant/ RER/ kg	Bimetallic busbars	**1757**	10047	2,54E-01	kg

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179	copper, primary, at refinery/ GLO/ kg	Bimetallic busbars	**1796**	10047	4,87E-01	kg
180	copper, secondary, at refinery/ RER/ kg	Bimetallic busbars	**1805**	10047	8,60E-02	kg
181	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	Bimetallic busbars	**2642**	10047	1,73E-01	kg
182	aluminium product manufacturing, average metal working/ RER/ kg	Bimetallic busbars	**1924**	10047	2,54E-01	kg
183	copper product manufacturing, average metal working/ RER/ kg	Bimetallic busbars	**1926**	10047	5,73E-01	kg
184	injection moulding/ RER/ kg	Bimetallic busbars	**2683**	10047	1,73E-01	kg
185	transport, freight, rail/ RER/ tkm	Bimetallic busbars	**2887**	10047	2,00E-01	tkm
186	transport, lorry >32t, EURO3/ RER/ tkm	Bimetallic busbars	**2809**	10047	1,00E-01	tkm
187	metal working factory/ RER/ unit	Bimetallic busbars	**3741**	10047	3,79E-10	p
188	plastics processing factory/ RER/ unit	Bimetallic busbars	**4006**	10047	1,28E-10	p
189	aluminium, production mix, at plant/ RER/ kg	Endbusbar, Al	**1757**	10048	9,09E-01	kg
190	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	Endbusbar, Al	**2642**	10048	9,09E-02	kg
191	aluminium product manufacturing, average metal working/ RER/ kg	Endbusbar, Al	**1924**	10048	9,09E-01	kg
192	injection moulding/ RER/ kg	Endbusbar, Al	**2683**	10048	9,09E-02	kg
193	transport, freight, rail/ RER/ tkm	Endbusbar, Al	**2887**	10048	2,00E-01	tkm
194	transport, lorry >32t, EURO3/ RER/ tkm	Endbusbar, Al	**2809**	10048	1,00E-01	tkm
195	aluminium casting, plant/ RER/ unit	Endbusbar, Al	**3713**	10048	1,40E-10	p
195	aluminium casting, plant/ RER/ unit	Endbusbar, Al	**3713**	10048	1,40E-10	p
196	plastics processing factory/ RER/ unit	Endbusbar, Al	**4006**	10048	6,73E-11	p
197	copper, primary, at refinery/ GLO/ kg	Endbusbar, Cu	**1796**	10049	8,24E-01	kg
198	copper, secondary, at refinery/ RER/ kg	Endbusbar, Cu	**1805**	10049	1,45E-01	kg
199	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg	Endbusbar, Cu	**2642**	10049	3,06E-02	kg
200	copper product manufacturing, average metal working/ RER/ kg	Endbusbar, Cu	**1926**	10049	9,69E-01	kg
201	injection moulding/ RER/ kg	Endbusbar, Cu	**2683**	10049	3,06E-02	kg
202	transport, freight, rail/ RER/ tkm	Endbusbar, Cu	**2887**	10049	2,00E-01	tkm
203	transport, lorry >32t, EURO3/ RER/ tkm	Endbusbar, Cu	**2809**	10049	1,00E-01	tkm
204	metal working factory/ RER/ unit	Endbusbar, Cu	**3741**	10049	4,44E-10	p
205	plastics processing factory/ RER/ unit	Endbusbar, Cu	**4006**	10049	2,27E-11	p

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206	aluminium, production mix, at plant/ RER/ kg	Aluminium "box"	**1757**	10050	1,00E+00	kg
207	aluminium product manufacturing, average metal working/ RER/ kg	Aluminium "box"	**1924**	10050	1,00E+00	kg
208	transport, freight, rail/ RER/ tkm	Aluminium "box"	**2887**	10050	2,00E-01	tkm
209	transport, lorry >32t, EURO3/ RER/ tkm	Aluminium "box"	**2809**	10050	1,00E-01	tkm
210	aluminium casting, plant/ RER/ unit	Aluminium "box"	**3713**	10050	0,00E+00	p
211	ethylene carbonate, at plant/ CN/ kg	Electrolyte	**701**	10051	8,84E-01	kg
212	transport, freight, rail/ RER/ tkm	Electrolyte	**2887**	10051	6,00E-01	tkm
213	transport, lorry >32t, EURO3/ RER/ tkm	Electrolyte	**2809**	10051	1,00E-01	tkm
214	chemical plant, organics/ RER/ unit	Electrolyte	**3641**	10051	4,00E-10	p
215	transport, freight, rail/ RER/ tkm	Cathode	**2887**	10052	5,54E-01	tkm
216	transport, lorry >32t, EURO3/ RER/ tkm	Cathode	**2809**	10052	1,00E-01	tkm
217	transport, freight, rail/ RER/ tkm	Anode	**2887**	10053	3,71E-01	tkm
218	transport, lorry >32t, EURO3/ RER/ tkm	Anode	**2809**	10053	1,00E-01	tkm
219	transport, freight, rail/ RER/ tkm	Cell container	**2887**	10054	2,00E-01	tkm
220	transport, lorry >32t, EURO3/ RER/ tkm	Cell container	**2809**	10054	1,00E-01	tkm
221	polypropylene, granulate, at plant/ RER/ kg	Separator	**2662**	10055	1,00E+00	kg
222	injection moulding/ RER/ kg	Separator	**2683**	10055	1,00E+00	kg
223	transport, freight, rail/ RER/ tkm	Separator	**2887**	10055	2,00E-01	tkm
224	transport, lorry >32t, EURO3/ RER/ tkm	Separator	**2809**	10055	1,00E-01	tkm
225	plastics processing factory/ RER/ unit	Separator	**4006**	10055	7,41E-10	p
226	aluminium, production mix, at plant/ RER/ kg	Positive current collector Al	**1757**	10056	1,00E+00	kg
227	sheet rolling, aluminium/ RER/ kg	Positive current collector Al	**1953**	10056	1,00E+00	kg
228	transport, freight, rail/ RER/ tkm	Positive current collector Al	**2887**	10056	2,00E-01	tkm
229	transport, lorry >32t, EURO3/ RER/ tkm	Positive current collector Al	**2809**	10056	1,00E-01	tkm
230	aluminium casting, plant/ RER/ unit	Positive current collector Al	**3713**	10056	1,54E-10	p
231	polyvinylfluoride, at plant/ US/ kg	Positive electrode paste	**777**	10057	4,00E-02	kg
232	carbon black, at plant/ GLO/ kg	Positive electrode paste	**465**	10057	2,00E-02	kg
233	N-methyl-2-pyrrolidone, at plant/ RER/ kg	Positive electrode paste	**636**	10057	4,07E-01	kg
234	transport, freight, rail/ RER/ tkm	Positive electrode paste	**2887**	10057	4,60E-01	tkm
235	transport, lorry >32t, EURO3/ RER/ tkm	Positive electrode paste	**2809**	10057	1,41E-01	tkm

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236	chemical plant, organics/ RER/ unit	Positive electrode paste	3641	10057	4,00E-10	p
237	copper, primary, at refinery/ GLO/ kg	Negative current collector Cu	1796	10058	8,50E-01	kg
238	copper, secondary, at refinery/ RER/ kg	Negative current collector Cu	1805	10058	1,50E-01	kg
239	sheet rolling, copper/ RER/ kg	Negative current collector Cu	1955	10058	1,00E+00	kg
240	transport, freight, rail/ RER/ tkm	Negative current collector Cu	2887	10058	2,00E-01	tkm
241	transport, lorry >32t, EURO3/ RER/ tkm	Negative current collector Cu	2809	10058	1,00E-01	tkm
242	metal working factory/ RER/ unit	Negative current collector Cu	3741	10058	4,58E-10	p
243	graphite, battery grade, at plant/ CN/ kg	Negative electrode paste	491	10059	9,60E-01	kg
244	carboxymethyl cellulose, powder, at plant/ RER/ kg	Negative electrode paste	2948	10059	2,00E-02	kg
245	acrylic acid, at plant/ RER/ kg	Negative electrode paste	649	10059	2,00E-02	kg
246	N-methyl-2-pyrrolidone, at plant/ RER/ kg	Negative electrode paste	636	10059	9,40E-01	kg
247	transport, freight, rail/ RER/ tkm	Negative electrode paste	2887	10059	1,16E+00	tkm
248	transport, lorry >32t, EURO3/ RER/ tkm	Negative electrode paste	2809	10059	1,94E-01	tkm
249	chemical plant, organics/ RER/ unit	Negative electrode paste	3641	10059	4,00E-10	p
250	aluminium, production mix, at plant/ RER/ kg	Tab, aluminum	1757	10060	1,00E+00	kg
251	sheet rolling, aluminium/ RER/ kg	Tab, aluminum	1953	10060	1,00E+00	kg
252	transport, freight, rail/ RER/ tkm	Tab, aluminum	2887	10060	2,00E-01	tkm
253	transport, lorry >32t, EURO3/ RER/ tkm	Tab, aluminum	2809	10060	1,00E-01	tkm
254	aluminium casting, plant/ RER/ unit	Tab, aluminum	3713	10060	1,54E-10	p
255	copper, primary, at refinery/ GLO/ kg	Tab, copper	1796	10061	8,50E-01	kg
255	copper, primary, at refinery/ GLO/ kg	Tab, copper	1796	10061	8,50E-01	kg
256	copper, secondary, at refinery/ RER/ kg	Tab, copper	1805	10061	1,50E-01	kg
257	sheet rolling, copper/ RER/ kg	Tab, copper	1955	10061	1,00E+00	kg
258	transport, freight, rail/ RER/ tkm	Tab, copper	2887	10061	2,00E-01	tkm
259	transport, lorry >32t, EURO3/ RER/ tkm	Tab, copper	2809	10061	1,00E-01	tkm
260	metal working factory/ RER/ unit	Tab, copper	3741	10061	4,58E-10	p
261	aluminium, production mix, at plant/ RER/ kg	Aluminum pouch	1757	10062	5,00E-01	kg
262	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg	Aluminum pouch	2653	10062	7,78E-02	kg
263	nylon 6, at plant/ RER/ kg	Aluminum pouch	2647	10062	7,99E-02	kg
264	polypropylene, granulate, at plant/ RER/ kg	Aluminum pouch	2662	10062	3,17E-01	kg
265	packaging film, LDPE, at plant/ RER/ kg	Aluminum pouch	2684	10062	2,53E-02	kg

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4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
266	injection moulding/ RER/ kg	Aluminum pouch	**2683**	10062	4,75E-01	kg
267	sheet rolling, aluminium/ RER/ kg	Aluminum pouch	**1953**	10062	5,00E-01	kg
268	aluminium casting, plant/ RER/ unit	Aluminum pouch	**3713**	10062	7,70E-11	p
269	plastics processing factory/ RER/ unit	Aluminum pouch	**4006**	10062	3,51E-10	p
270	lithium hydroxide, at plant/ GLO/ kg	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**521**	10063	2,49E-01	kg
271	heat, unspecific, in chemical plant/ RER/ MJ	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**728**	10063	5,50E-01	MJ
272	transport, freight, rail/ RER/ tkm	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**2887**	10063	7,19E-01	tkm
273	transport, lorry >16t, fleet average/ RER/ tkm	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**2807**	10063	1,20E-01	tkm
274	chemical plant, organics/ RER/ unit	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**3641**	10063	4,00E-10	p
275	soda, powder, at plant/ RER/ kg	Ni(1/3)Co(1/3)Mn(1/3)	**567**	10064	8,77E-01	kg
276	transport, freight, rail/ RER/ tkm	Ni(1/3)Co(1/3)Mn(1/3)	**2887**	10064	1,54E+00	tkm
277	transport, lorry >16t, fleet average/ RER/ tkm	Ni(1/3)Co(1/3)Mn(1/3)	**2807**	10064	2,56E-01	tkm
278	chemical plant, organics/ RER/ unit	Ni(1/3)Co(1/3)Mn(1/3)	**3641**	10064	4,00E-10	p
279	ammonia, liquid, at regional storehouse/ RER/ kg	Nickel Sulphate	**444**	10065	3,17E-02	kg
280	chemicals inorganic, at plant/ GLO/ kg	Nickel Sulphate	**469**	10065	2,33E-02	kg
281	chemicals organic, at plant/ GLO/ kg	Nickel Sulphate	**673**	10065	6,83E-03	kg
282	hydrogen cyanide, at plant/ RER/ kg	Nickel Sulphate	**733**	10065	1,06E-03	kg
283	hydrogen, liquid, at plant/ RER/ kg	Nickel Sulphate	**504**	10065	0,00E+00	kg
284	limestone, milled, packed, at plant/ CH/ kg	Nickel Sulphate	**880**	10065	7,31E-01	kg
285	portland calcareous cement, at plant/ CH/ kg	Nickel Sulphate	**841**	10065	9,96E-01	kg
286	sand, at mine/ CH/ kg	Nickel Sulphate	**830**	10065	1,26E+01	kg
287	silica sand, at plant/ DE/ kg	Nickel Sulphate	**831**	10065	7,17E-01	kg
288	blasting/ RER/ kg	Nickel Sulphate	**892**	10065	4,57E-02	kg
289	diesel, burned in building machine/ GLO/ MJ	Nickel Sulphate	**896**	10065	3,08E+00	MJ
290	electricity, high voltage, production UCTE, at grid/ UCTE/ kWh	Nickel Sulphate	**936**	10065	1,14E+00	kWh
291	electricity, hydropower, at run-of-river power plant/ RER/ kWh	Nickel Sulphate	**1553**	10065	2,91E+00	kWh
292	electricity, medium voltage, production UCTE, at grid/ UCTE/ kWh	Nickel Sulphate	**1002**	10065	4,79E-01	kWh
293	heat, at hard coal industrial furnace 1-10MW/ RER/ MJ	Nickel Sulphate	**1393**	10065	7,09E-01	MJ
294	heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	Nickel Sulphate	**2394**	10065	8,14E+00	MJ
295	natural gas, burned in industrial furnace >100kW/ RER/ MJ	Nickel Sulphate	**2129**	10065	3,47E+00	MJ

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3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
296	aluminium hydroxide, plant/ RER/ unit	Nickel Sulphate	3715	10065	2,54E-10	p
297	conveyor belt, at plant/ RER/ m	Nickel Sulphate	3660	10065	1,16E-06	m3
298	non-ferrous metal mine, underground/ GLO/ unit	Nickel Sulphate	3738	10065	1,51E-09	p
299	non-ferrous metal smelter/ GLO/ unit	Nickel Sulphate	3739	10065	1,27E-11	p
300	transport, lorry >16t, fleet average/ RER/ tkm	Nickel Sulphate	2807	10065	6,83E-01	tkm
301	disposal, nickel smelter slag, 0% water, to residual material landfill/ CH/ kg	Nickel Sulphate	3300	10065	3,63E+00	kg
302	disposal, sulfidic tailings, off-site/ GLO/ kg	Nickel Sulphate	3315	10065	2,75E+01	kg
303	carbon monoxide, CO, at plant/ RER/ kg	Cobalt Sulphate	467	10066	0,00E+00	kg
304	chemicals inorganic, at plant/ GLO/ kg	Cobalt Sulphate	469	10066	3,23E-02	kg
305	chemicals organic, at plant/ GLO/ kg	Cobalt Sulphate	673	10066	9,51E-03	kg
306	hydrogen cyanide, at plant/ RER/ kg	Cobalt Sulphate	733	10066	1,49E-03	kg
307	hydrogen, liquid, at plant/ RER/ kg	Cobalt Sulphate	504	10066	0,00E+00	kg
308	limestone, milled, packed, at plant/ CH/ kg	Cobalt Sulphate	880	10066	1,90E-02	kg
309	portland calcareous cement, at plant/ CH/ kg	Cobalt Sulphate	841	10066	1,38E+00	kg
310	sand, at mine/ CH/ kg	Cobalt Sulphate	830	10066	1,73E+01	kg
311	blasting/ RER/ kg	Cobalt Sulphate	892	10066	6,31E-02	kg
312	diesel, burned in building machine/ GLO/ MJ	Cobalt Sulphate	896	10066	4,60E+00	MJ
313	electricity, medium voltage, production UCTE, at grid/ UCTE/ kWh	Cobalt Sulphate	1002	10066	1,78E+00	kWh
314	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	Cobalt Sulphate	2118	10066	0,00E+00	MJ
315	aluminium hydroxide, plant/ RER/ unit	Cobalt Sulphate	3715	10066	3,42E-10	p
316	conveyor belt, at plant/ RER/ m	Cobalt Sulphate	3660	10066	1,60E-06	m3
317	non-ferrous metal mine, underground/ GLO/ unit	Cobalt Sulphate	3738	10066	2,09E-09	p
318	transport, lorry >16t, fleet average/ RER/ tkm	Cobalt Sulphate	2807	10066	9,43E-01	tkm
319	disposal, non-sulfidic overburden, off-site/ GLO/ kg	Cobalt Sulphate	3301	10066	1,33E+01	kg
320	disposal, non-sulfidic tailings, off-site/ GLO/ kg	Cobalt Sulphate	3302	10066	2,47E+01	kg
321	manganese concentrate, at beneficiation/ GLO/ kg	Manganese Sulphate	1845	10067	1,07E+00	kg
322	sulphuric acid, liquid, at plant/ RER/ kg	Manganese Sulphate	603	10067	6,50E-01	kg
323	natural gas, high pressure, at consumer/ CH/ MJ	Manganese Sulphate	2088	10067	3,63E-02	MJ
324	hard coal coke, at plant/ RER/ MJ	Manganese Sulphate	1382	10067	1,43E+00	MJ
325	electricity, medium voltage, production UCTE, at grid/ UCTE/ kWh	Manganese Sulphate	1002	10067	2,14E-02	kWh

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3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
326	transport, freight, rail/ RER/ tkm	Manganese Sulphate	**2887**	10067	3,90E-01	tkm
327	transport, lorry >16t, fleet average/ RER/ tkm	Manganese Sulphate	**2807**	10067	6,50E-02	tkm
328	non-ferrous metal smelter/ GLO/ unit	Manganese Sulphate	**3739**	10067	1,06E-14	p
329	aluminium hydroxide, plant/ RER/ unit	Manganese Sulphate	**3715**	10067	2,44E-10	p
330	disposal, non-sulfidic tailings, off-site/ GLO/ kg	Manganese Sulphate	**3302**	10067	7,06E-01	kg
331	hydrogen fluoride, at plant/ GLO/ kg	Lithium hexafluorophosphate	**499**	10068	4,04E+00	kg
332	nitrogen, liquid, at plant/ RER/ kg	Lithium hexafluorophosphate	**530**	10068	1,25E-03	kg
333	lime, hydrated, packed, at plant/ CH/ kg	Lithium hexafluorophosphate	**839**	10068	7,44E+00	kg
334	electricity, medium voltage, at grid/ CN/ kWh	Lithium hexafluorophosphate	**1169**	10068	1,50E-01	kWh
335	transport, freight, rail/ RER/ tkm	Lithium hexafluorophosphate	**2887**	10068	8,19E+00	tkm
336	transport, lorry >16t, fleet average/ RER/ tkm	Lithium hexafluorophosphate	**2807**	10068	1,37E+00	tkm
337	chemical plant, organics/ RER/ unit	Lithium hexafluorophosphate	**3641**	10068	4,00E-10	p
338	disposal, limestone residue, 5% water, to inert material landfill/ CH/ kg	Lithium hexafluorophosphate	**3079**	10068	8,61E+00	kg
339	treatment, sewage, to wastewater treatment, class 1/ CH/ m3	Lithium hexafluorophosphate	**3376**	10068	3,61E-03	m3
340	hydrogen fluoride, at plant/ GLO/ kg	LiF	**499**	10069	8,06E-01	kg
341	ammonia, liquid, at regional storehouse/ RER/ kg	LiF	**444**	10069	3,28E-02	kg
342	water, deionised, at plant/ CH/ kg	LiF	**3390**	10069	2,21E+00	kg
343	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	LiF	**2118**	10069	1,21E+00	MJ
344	transport, freight, rail/ RER/ tkm	LiF	**2887**	10069	1,38E+00	tkm
345	transport, lorry >16t, fleet average/ RER/ tkm	LiF	**2807**	10069	2,33E-01	tkm
346	chemical plant, organics/ RER/ unit	LiF	**3641**	10069	4,00E-10	p
347	treatment, sewage, to wastewater treatment, class 1/ CH/ m3	LiF	**3376**	10069	3,57E-03	m3
348	phosphorous chloride, at plant/ RER/ kg	PCl5	**540**	10070	7,03E-01	kg
349	chlorine, liquid, production mix, at plant/ RER/ kg	PCl5	**475**	10070	3,63E-01	kg
350	electricity, medium voltage, at grid/ CN/ kWh	PCl5	**1169**	10070	5,56E-04	kWh
351	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	PCl5	**2118**	10070	8,67E-02	MJ
352	transport, freight, rail/ RER/ tkm	PCl5	**2887**	10070	4,58E-01	tkm
353	transport, lorry >16t, fleet average/ RER/ tkm	PCl5	**2807**	10070	1,07E-01	tkm
354	chemical plant, organics/ RER/ unit	PCl5	**3641**	10070	4,00E-10	p
355	concentrated lithium brine (6.7 % Li), at plant/ GLO/ kg	Lithium carbonate	**477**	10071	9,38E+00	kg

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3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*
356	quicklime, milled, loose, at plant/ CH/ kg	Lithium carbonate	**826**	10071	1,76E-01	kg
357	sulphuric acid, liquid, at plant/ RER/ kg	Lithium carbonate	**603**	10071	3,57E-02	kg
358	hydrochloric acid, 30% in H2O, at plant/ RER/ kg	Lithium carbonate	**494**	10071	5,71E-02	kg
359	bentonite, at processing/ DE/ kg	Lithium carbonate	**811**	10071	1,44E-02	kg
360	2-methyl-2-butanol, at plant/ RER/ kg	Lithium carbonate	**627**	10071	1,19E-03	kg
361	soda, powder, at plant/ RER/ kg	Lithium carbonate	**567**	10071	3,73E+00	kg
362	solvents, organic, unspecified, at plant/ GLO/ kg	Lithium carbonate	**787**	10071	4,75E-03	kg
363	sodium hydroxide, 50% in H2O, production mix, at plant/ RER/ kg	Lithium carbonate	**580**	10071	1,88E-04	kg
364	electricity, medium voltage, at grid/ BR/ kWh	Lithium carbonate	**1168**	10071	1,56E-04	kWh
365	heat, natural gas, at industrial furnace >100kW/ RER/ MJ	Lithium carbonate	**2118**	10071	6,09E+00	MJ
366	natural gas, high pressure, at consumer/ RER/ MJ	Lithium carbonate	**2089**	10071	-2,00E+00	MJ
367	natural gas, liquefied, at freight ship/ JP/ Nm3	Lithium carbonate	**2226**	10071	9,53E-05	Nm3
368	diesel, burned in building machine/ GLO/ MJ	Lithium carbonate	**896**	10071	2,84E-01	MJ
369	transport, lorry 16-32t, EURO3/ RER/ tkm	Lithium carbonate	**2794**	10071	2,59E+00	tkm
370	transport, lorry 7.5-16t, EURO3/ RER/ tkm	Lithium carbonate	**2804**	10071	2,40E-03	tkm
371	chemical plant, organics/ RER/ unit	Lithium carbonate	**3641**	10071	4,00E-10	p
372	disposal, hazardous waste, 0% water, to underground deposit/ DE/ kg	Lithium carbonate	**3350**	10071	2,05E-04	kg

1 2	***In this sheet, you enter the coordinates of the requirements placed on the background by the foreground. This will be assembled as an A_bf matrix***					
3 4	**Background Name** *Comment*	**Foreground Process Name** *Comment*	**(Arda ID)** **BACKGROUND ID**	**(Process ID)** **FOREGROUND ID**	**AMOUNT**	**Unit** *Comment*
373	disposal, decarbonising waste, 30% water, to residual material landfill/ CH/ kg	Lithium carbonate	**3279**	10071	6,41E+00	kg
374	zinc, primary, at regional storage/ RER/ kg	Op. CONV	**1923**	10002	3,74E-04	kg
375	alkyd paint, white, 60% in solvent, at plant/ RER/ kg	Op. CONV	**2486**	10002	8,89E-03	kg
376	lubricating oil, at plant/ RER/ kg	Op. CONV	**740**	10002	2,36E-01	kg
377	aluminium, secondary, from new scrap, at plant/ RER/ kg	Hull El	**1760**	10013	4,20E+05	kg
378	steel, low-alloyed, at plant/ RER/ kg	Hull CONV	**1914**	10014	1,00E+06	kg
379	lubricating oil, at plant/ RER/ kg	Op. Gas_Ampere	**740**	10003	7,41E-02	kg
380	lubricating oil, at plant/ RER/ kg	Op. Diesel_Ampere	**740**	10004	1,48E-01	kg
381	steel, low-alloyed, at plant/ RER/ kg	Engine conv, large	**1914**	10016	4,30E+03	kg
382	aluminium, secondary, from new scrap, at plant/ RER/ kg	Engine conv, large	**1760**	10016	1,28E+02	kg
383	steel, low-alloyed, at plant/ RER/ kg	engine small	**1914**	10017	3,99E+03	kg
384	aluminium, secondary, from new scrap, at plant/ RER/ kg	engine small	**1760**	10017	1,19E+02	kg
385	electricity, low voltage, production NO, at grid/ NO/ kWh	Op. Gas_Ampere	**960**	10003	1,17E+00	kWh
386	electricity, low voltage, production NO, at grid/ NO/ kWh	Op. Diesel_Ampere	**960**	10004	1,17E+00	kWh

S_f, direct stressors from foreground prosesses

1 2	***In this sheet, you enter direct stressor emissions of the foreground. The indexes will be assembled as an F_f (also called S_f) matrix.***					
3	**Stressor Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**	**(Value)**	**UNIT**
4	*Comment*	*Comment*	**STRESSOR ID**	**FOREGROUND ID**	**AMOUNT**	Comment
8	particulates, < 2.5 um, air, low population density, kg	Op. CONV	**393**	10002	9,86E-02	kg
9	zinc, ion, water, ocean, kg	Op. CONV	**1602**	10002	0,000374392	kg
10	carbon monoxide, fossil, air, low population density, kg	Op. CONV	**123**	10002	1,82E-01	kg
11	methane, fossil, air, low population density, kg	Op. CONV	**337**	10002	3,94E-03	kg
12	nitrous oxide, air, low population density, kg	Op. CONV	**175**	10002	9,86E-03	kg
13	nmvoc, non-methane volatile organic compounds, unspecified origin, air, low population density, kg	Op. CONV	**366**	10002	2,02E-01	kg
14	carbon dioxide, fossil, air, low population density, kg	Op. Gas_Ampere	**112**	10003	1,26E+02	kg
15	nox to air, air, low population density, kg	Op. Gas_Ampere	**381**	10003	2,57E-01	kg
16	so2 to air, air, unspecified, kg	Op. Gas_Ampere	**506**	10003	9,18E-04	kg
17	particulates, < 2.5 um, air, low population density, kg	Op. Gas_Ampere	**393**	10003	8,26E-03	kg
18	carbon monoxide, fossil, air, low population density, kg	Op. Gas_Ampere	**123**	10003	3,59E-01	kg
19	methane, fossil, air, low population density, kg	Op. Gas_Ampere	**337**	10003	1,82E+00	kg
20	nitrous oxide, air, low population density, kg	Op. Gas_Ampere	**175**	10003	5,05E-03	kg
21	nmvoc, non-methane volatile organic compounds, unspecified origin, air, low population density, kg	Op. Gas_Ampere	**366**	10003	1,38E-01	kg
22	carbon dioxide, fossil, air, low population density, kg	Op. Diesel_Ampere	**112**	10004	129,5949323	kg
23	nox to air, air, low population density, kg	Op. Diesel_Ampere	**381**	10004	2,02E+00	kg
24	so2 to air, air, unspecified, kg	Op. Diesel_Ampere	**506**	10004	7,90E+00	kg
25	particulates, < 2.5 um, air, low population density, kg	Op. Diesel_Ampere	**393**	10004	6,06E-02	kg

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3	**Stressor Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**	**(Value)**	**UNIT**
4	*Comment*	*Comment*	**STRESSOR ID**	**FOREGROUND ID**	**AMOUNT**	Comment (
26	carbon monoxide, fossil, air, low population density, kg	Op. Diesel_Ampere	**123**	10004	1,12E-01	kg
27	methane, fossil, air, low population density, kg	Op. Diesel_Ampere	**337**	10004	2,43E-03	kg
28	nitrous oxide, air, low population density, kg	Op. Diesel_Ampere	**175**	10004	6,06E-03	kg
29	nmvoc, non-methane volatile organic compounds, unspecified origin, air, low population density, kg	Op. Diesel_Ampere	**366**	10004	1,25E-01	kg
30	Heat, waste/ air/ unspecified	Marine battery	**240**	10021	1,8E-05	MJ
31	Heat, waste/ air/ unspecified	Battery cell	**240**	10025	1,6E+00	MJ
32	Sulfur hexafluoride/air	Battery cell	**509**	10025	2,1E-06	kg
33	Heat, waste/soil	Battery cell	**964**	10025	5,2E-01	MJ
34	Dinitrogen monoxide/air	Battery cell	**177**	10025	1,5E-04	kg
35	Ozone/air	Battery cell	**387**	10025	1,3E-04	kg
36	Heat, waste/ air/ unspecified	Li[Ni(1/3)Co(1/3)Mn(1/3)]O2	**240**	10063	5,5E-01	MJ
37	Nickel_ 1.13% in sulfide_ Ni 0.76% and Cu 0.76% in crude ore_ in ground	Emissions NiSO4	**665**	10065	4,8E-01	kg
38	Cobalt_ in ground	Emissions NiSO4	**599**	10065	0,0E+00	kg
39	Water_ river	Emissions NiSO4	**800**	10065	1,1E-02	m3
40	Water_ well_ in ground	Emissions NiSO4	**805**	10065	6,1E-02	m3
41	Aluminum	Emissions NiSO4	**37**	10065	5,6E-04	kg
42	Arsenic	Emissions NiSO4	**54**	10065	2,0E-06	kg
43	Calcium	Emissions NiSO4	**106**	10065	3,9E-04	kg
44	Carbon dioxide_ fossil	Emissions NiSO4	**114**	10065	3,2E-01	kg
45	Carbon disulfide	Emissions NiSO4	**118**	10065	3,0E-03	kg
46	Cobalt	Emissions NiSO4	**153**	10065	4,2E-04	kg
47	Copper	Emissions NiSO4	**160**	10065	1,3E-04	kg
48	Dioxins_ measured as 2_3_7_8-tetrachlorodibenzo-p-dioxin	Emissions NiSO4	**180**	10065	3,5E-12	kg
49	Heat_ waste	Emissions NiSO4	**240**	10065	2,0E+01	MJ
50	Lead	Emissions NiSO4	**302**	10065	1,2E-05	kg
51	Magnesium	Emissions NiSO4	**313**	10065	3,3E-04	kg
52	Nickel	Emissions NiSO4	**373**	10065	1,5E-04	kg
53	NMVOC_ non-methane volatile organic compounds_ unspecified origin	Emissions NiSO4	**368**	10065	6,9E-05	kg
54	Particulates_ < 2.5 um	Emissions NiSO4	**396**	10065	5,7E-03	kg
55	Particulates_ > 10 um	Emissions NiSO4	**400**	10065	5,8E-04	kg
56	Particulates_ > 2.5 um_ and < 10um	Emissions NiSO4	**404**	10065	5,0E-03	kg
57	Silver	Emissions NiSO4	**480**	10065	4,8E-08	kg
58	Sulfur dioxide	Emissions NiSO4	**506**	10065	5,1E-01	kg
59	Tin	Emissions NiSO4	**531**	10065	2,3E-06	kg
60	Zinc	Emissions NiSO4	**573**	10065	3,5E-05	kg
61	Aluminum	Emissions NiSO4	**1168**	10065	5,2E-06	kg
62	Arsenic_ ion	Emissions NiSO4	**1187**	10065	2,6E-07	kg

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	Stressor Name	Foreground Process Name	(Arda ID)	(Process ID)	(Value)	UNIT
	Comment	*Comment*	STRESSOR ID	FOREGROUND ID	AMOUNT	Comment
62	Arsenic_ ion	Emissions NiSO4	**1187**	10065	2,6E-07	kg
63	BOD5_ Biological Oxygen Demand	Emissions NiSO4	**1192**	10065	6,3E-04	kg
64	Cadmium_ ion	Emissions NiSO4	**1241**	10065	3,1E-08	kg
65	Calcium_ ion	Emissions NiSO4	**1247**	10065	1,3E-02	kg
66	Calcium_ ion	Emissions NiSO4	**1244**	10065	2,9E-02	kg
67	Chromium_ ion	Emissions NiSO4	**1282**	10065	1,6E-07	kg
68	Cobalt	Emissions NiSO4	**1288**	10065	4,7E-08	kg
69	COD_ Chemical Oxygen Demand	Emissions NiSO4	**1235**	10065	6,3E-04	kg
70	Copper_ ion	Emissions NiSO4	**1297**	10065	7,1E-07	kg
71	Cyanide	Emissions NiSO4	**1301**	10065	1,1E-04	kg
72	DOC_ Dissolved Organic Carbon	Emissions NiSO4	**1307**	10065	2,5E-04	kg
73	Iron_ ion	Emissions NiSO4	**1373**	10065	1,8E-05	kg
74	Lead	Emissions NiSO4	**1383**	10065	2,4E-07	kg
75	Manganese	Emissions NiSO4	**1389**	10065	1,5E-06	kg
76	Mercury	Emissions NiSO4	**1399**	10065	3,5E-09	kg
77	Nickel_ ion	Emissions NiSO4	**1428**	10065	1,6E-06	kg
78	Nitrogen_ organic bound	Emissions NiSO4	**1442**	10065	1,4E-03	kg
79	Nitrogen	Emissions NiSO4	**1439**	10065	0,0E+00	kg
80	Solved solids	Emissions NiSO4	**1543**	10065	3,1E-04	kg
81	Sulfate	Emissions NiSO4	**1533**	10065	1,4E-01	kg
82	Tin_ ion	Emissions NiSO4	**1566**	10065	1,2E-07	kg
83	TOC_ Total Organic Carbon	Emissions NiSO4	**1548**	10065	2,5E-04	kg
84	Zinc_ ion	Emissions NiSO4	**1604**	10065	5,0E-06	kg
85	Nickel_ 1.13% in sulfide_ Ni 0.76% and Cu 0.76% in crude ore_ in ground	Emissions CoSO4	**665**	10066	0,0E+00	kg
86	Cobalt_ in ground	Emissions CoSO4	**599**	10066	5,0E-01	kg
87	Water_ river	Emissions CoSO4	**800**	10066	1,4E-02	m3
88	Water_ well_ in ground	Emissions CoSO4	**805**	10066	8,4E-02	m3
89	Aluminum	Emissions CoSO4	**37**	10066	0,0E+00	kg
90	Arsenic	Emissions CoSO4	**54**	10066	0,0E+00	kg
91	Calcium	Emissions CoSO4	**106**	10066	0,0E+00	kg
92	Carbon dioxide_ fossil	Emissions CoSO4	**114**	10066	0,0E+00	kg
93	Carbon disulfide	Emissions CoSO4	**118**	10066	4,2E-03	kg
94	Cobalt	Emissions CoSO4	**153**	10066	0,0E+00	kg
95	Copper	Emissions CoSO4	**160**	10066	0,0E+00	kg
96	Dioxins_ measured as 2_3_7_8-tetrachlorodibenzo-p-dioxin	Emissions CoSO4	**180**	10066	0,0E+00	kg
97	Heat_ waste	Emissions CoSO4	**240**	10066	6,4E+00	MJ
98	Lead	Emissions CoSO4	**302**	10066	0,0E+00	kg
99	Magnesium	Emissions CoSO4	**313**	10066	0,0E+00	kg
100	Nickel	Emissions CoSO4	**373**	10066	0,0E+00	kg
101	NMVOC_ non-methane volatile organic compounds_ unspecified origin	Emissions CoSO4	**368**	10066	0,0E+00	kg
102	Particulates_ < 2.5 um	Emissions CoSO4	**396**	10066	7,5E-04	kg
103	Particulates_ > 10 um	Emissions CoSO4	**400**	10066	7,7E-03	kg
104	Particulates_ > 2.5 um_ and < 10um	Emissions CoSO4	**404**	10066	6,7E-03	kg
105	Silver	Emissions CoSO4	**480**	10066	0,0E+00	kg
106	Sulfur dioxide	Emissions CoSO4	**506**	10066	0,0E+00	kg

1	*In this sheet, you enter direct stressor emissions of the foreground. The indexes will be*						
2	*assembled as an F_f (also called S_f) matrix.*						
3	**Stressor Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**	**(Value)**	**UNIT**	
4	*Comment*	*Comment*	**STRESSOR ID**	**FOREGROUND ID**	**AMOUNT**	Comment	
107	Tin	Emissions CoSO4	**531**	10066	0,0E+00	kg	
108	Zinc	Emissions CoSO4	**573**	10066	0,0E+00	kg	
109	Aluminum	Emissions CoSO4	**1168**	10066	7,2E-06	kg	
110	Arsenic_ ion	Emissions CoSO4	**1187**	10066	2,5E-07	kg	
111	BOD5_ Biological Oxygen Demand	Emissions CoSO4	**1192**	10066	0,0E+00	kg	
112	Cadmium_ ion	Emissions CoSO4	**1241**	10066	2,6E-08	kg	
113	Calcium_ ion	Emissions CoSO4	**1247**	10066	5,7E-02	kg	
114	Calcium_ ion	Emissions CoSO4	**1244**	10066	0,0E+00	kg	
115	Chromium_ ion	Emissions CoSO4	**1282**	10066	4,6E-08	kg	
116	Cobalt	Emissions CoSO4	**1288**	10066	6,5E-08	kg	
117	COD_ Chemical Oxygen Demand	Emissions CoSO4	**1235**	10066	8,7E-04	kg	
118	Copper_ ion	Emissions CoSO4	**1297**	10066	6,7E-07	kg	
119	Cyanide	Emissions CoSO4	**1301**	10066	1,6E-04	kg	
120	DOC_ Dissolved Organic Carbon	Emissions CoSO4	**1307**	10066	0,0E+00	kg	
121	Iron_ ion	Emissions CoSO4	**1373**	10066	2,4E-05	kg	
122	Lead	Emissions CoSO4	**1383**	10066	2,3E-07	kg	
123	Manganese	Emissions CoSO4	**1389**	10066	2,1E-06	kg	
124	Mercury	Emissions CoSO4	**1399**	10066	3,2E-09	kg	
125	Nickel_ ion	Emissions CoSO4	**1428**	10066	2,0E-06	kg	
126	Nitrogen_ organic bound	Emissions CoSO4	**1442**	10066	0,0E+00	kg	
127	Nitrogen	Emissions CoSO4	**1439**	10066	1,9E-03	kg	
128	Solved solids	Emissions CoSO4	**1543**	10066	4,3E-04	kg	
129	Sulfate	Emissions CoSO4	**1533**	10066	2,0E-01	kg	
130	Tin_ ion	Emissions CoSO4	**1566**	10066	0,0E+00	kg	
131	TOC_ Total Organic Carbon	Emissions CoSO4	**1548**	10066	0,0E+00	kg	
132	Zinc_ ion	Emissions CoSO4	**1604**	10066	6,4E-06	kg	
133	Heat, waste/ air/ unspecified	Manganese Sulphate	**240**	10067	1,5E+00	MJ	
134	Phosphorus trichloride/ air/ high population density	Lithium hexafluorophosphate	**420**	10068	2,6E-01	kg	
135	Heat, waste/ air/ unspecified	Lithium hexafluorophosphate	**240**	10068	2,0E+00	MJ	
136	Hydrogen fluoride/ air/ high population density	LiF	**268**	10069	3,6E-02	kg	
137	Ammonium, ion/ water/ unspecified	LiF	**1173**	10069	3,5E-02	kg	
138	Carbon dioxide, fossil/ air/ unspecified	LiF	**114**	10069	8,9E-01	kg	
139	Phosphorus trichloride/ air/ high population density	PCl5	**420**	10070	4,3E-02	kg	
140	Chlorine/ air/ high population density	PCl5	**131**	10070	2,2E-02	kg	
141	Heat, waste/ air/ unspecified	PCl5	**240**	10070	7,2E-03	MJ	
142	Heat, waste/ air/ unspecified	Lithium carbonate	**240**	10071	2,0E-03	MJ	

Appendix B – Resistance Calculations

MF Oppedal

Guldhammer/Harvald		
Slankhetstall	8,243432144	
Fn	0,173839019	
Cp	0,607552566	
R_n	324539139,7	
Leser av Cr		
C_R	2,00E-04	
C_F	1,77E-03	ITTC
C_A	3,80E-04	skalaeffekt
C_B/T	3,91E-04	
C_bulb	0	
C_T	0,002739598	
R_T	59,81597462	kN
P_e	338,4627108	kW
P_B	**593,4194382**	**kW**

	Fn	0,17383902						
	Rn	3,25E+08						
Viskøs motstand								
friksjon	Cf	0,00176901	ITTC'57					
form	k	-0,0682547	MARINTEK	phi	0,03714		Holltrops formel	
				k	0,01	avlest	1+k	0,9317
							L_cb	0
							C_14	0,945
							C_stevn	-5
							L_R	72,418
							C_P	0,3645
ruhet	deltaCf	0,00024593	150nym		8,51127			
appendix								
Bølgemotstand								
	Cr	0,0008	Rounded value from paper by marintek load on azimuth 30/70 (bow/stern)					
Luftmotstand								
C_AA								
C_T	0,002677							
RT	5,85E+04	N						
	58	kN						
Pe	331	kW						
propulsjonsvirkni	0,51							
Pd	648,5877	kW						
el-tap virkningsgr	0,9							
mekanisk tap	0,95							
Pb	758,5821	kW						

MS Ampere

main dimensions				
	lightship	1000	t	assumed
	payload	600	t	assumed
	LOA	79,4	m	
	LPP	78,6	m	
	B	20,8	m	
	D	6	m	
	T	3,7	m	

	Volumetric displacement	1560,976	m^3	
	C_B	0,258053		
	S	1040,197		

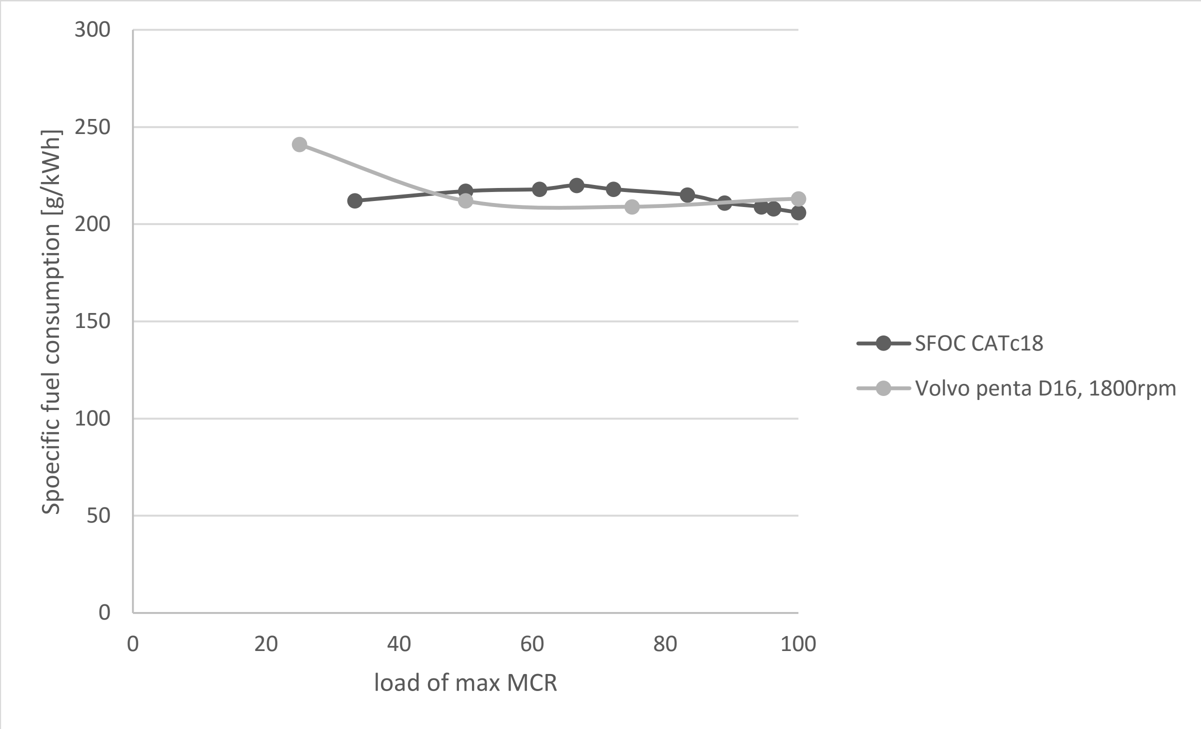
Guldhammer/Harvald		May be inaccurate method, but the result is confimed by unofficial sources
Slankhetstall	6,639369885	
Fn	0,1871416	
Cp	0,438922224	
R_n	210398615	
Leser av Cr		
C_R	4,00E-04	
C_F	1,88E-03	ITTC
C_A	4,00E-04	skalaeffekt
C_B/T	-3,14E-04	
C_bulb	0	
C_T	0,002362384	
R_T	35	kN

Pe	180	kW
propulsjonsvirkningsgrad	0,51	
Pd	353,0196	kW
el-tap virkningsgrad	0,835	
mekanisk tap	0,95	
Pb	**445,0294**	kW

Appendix C – Fuel Consumption

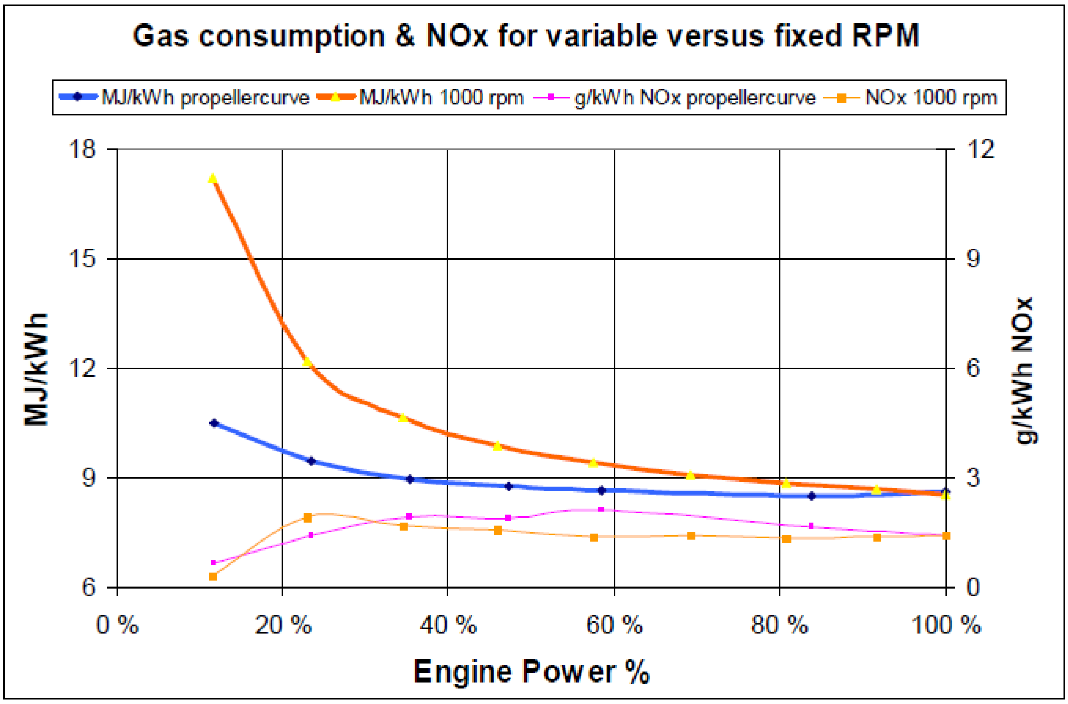
MF Oppedal

Consumers	Installed power	*available power [kW]*	LF	Manuvering	LF	Aceleration/ d	LF	transit	LF	decelerat	LF	manuveri	LF	at port
Auxilaries		*100*	1	100	1	100	1	100	1	100	1	100	1	100
Propulsion		*758,5821*	0,5	379,2910479	1,2	910,298515	1	758,582096	0,25	189,6455	0,5	379,291	0,1	75,85820958
sum		858,5821		479,2910479		1010,298515		858,582096		289,6455		479,291		175,8582096
		1100	%MCR	0,435719134		0,918453195		0,78052918		0,263314		0,435719		0,319742199
			#kWh during lifetime	4480652,361		12143283		104098632		3481394		4480652		13437181,51
			SFOC_variable speed/rpm [g/kWh]	220		220		220		240		220		239
			Fuel consumed during lifetime	985743519,5		2671522260		2,2902E+10		8,36E+08		9,86E+08		3211486381
			Total fuel concumed during vessel life	3,16E+10	g	**3,16E+07 kg**		**Fuel per trip [kg]**	6,57E+01					



MS Ampere on MDO

LF	Manuvering	LF	Aceleratio	LF	transit	LF	deceleratio	LF	manuverin	LF	at port
1	85	1	85	1	85	1	85	1	85	1	85
0,5	222,5147229	1,2	534,03533	1	445,029446	0,25	111,25736	0,5	222,51472	0	0
	307,5147229		619,03533		530,029446		196,25736		307,51472		85
%MCR	0,439306747		0,8843362		0,75718492		0,2803677		0,4393067		0,24285714
#kWh during lifetime	1231903,98		3719783		54603100		1179310		1231904		4863786
SFOC_variable speed/rpm [MJ/kWh]	16		13		13		14		16		15
MJ gas consumed during lifetime	19710463,68		48357183		709840302		16510347		19710464		72956782,9
Total fuel concumed during 1 x trip	2,46E+03	MJ	**4,59E+01**	**kg**	1,02E+02	l	1,02E-01	m^3	1,39E+01	6,24E+00	



Rolls-Royce K-engine

For gas consumption, engine data suggests larger consumption for a smaller engine than RR K-engine, the curve is therefore scaled by + 3 MJ/kWH

Appendix D – Calculation of Combustive Stressors

MF Oppedal

Nox	max rpm	1800										
	rpm at operational mode	784,294442		1653,2158		1404,9525		473,9654		784,29444		575,535959
	IMO Tier II											
	NOx [g/kWh]	11,86633723		10,222253		10,560396		13,123908		11,866337		12,6240301
	NOx [g/lifetime]	53168931,92		124131706		1,099E+09		45689500		53168932		169631384
	NOx	1545113181	g	1,55E+06	kg							
		3213,763429		3,21E+00	kg	3,86E+01	/year if ampere# crossings					

CO_2			
	CF (t-CO2/t-Fuel)	3,206	MEPC
	CO_2	**210664,0967**	**ton**
		210,6640967	**kg**
SO2, calculated using IMO			
	sulfur mass% in fuel	0,1	
	SO_2	**1,28E+01**	**kg**

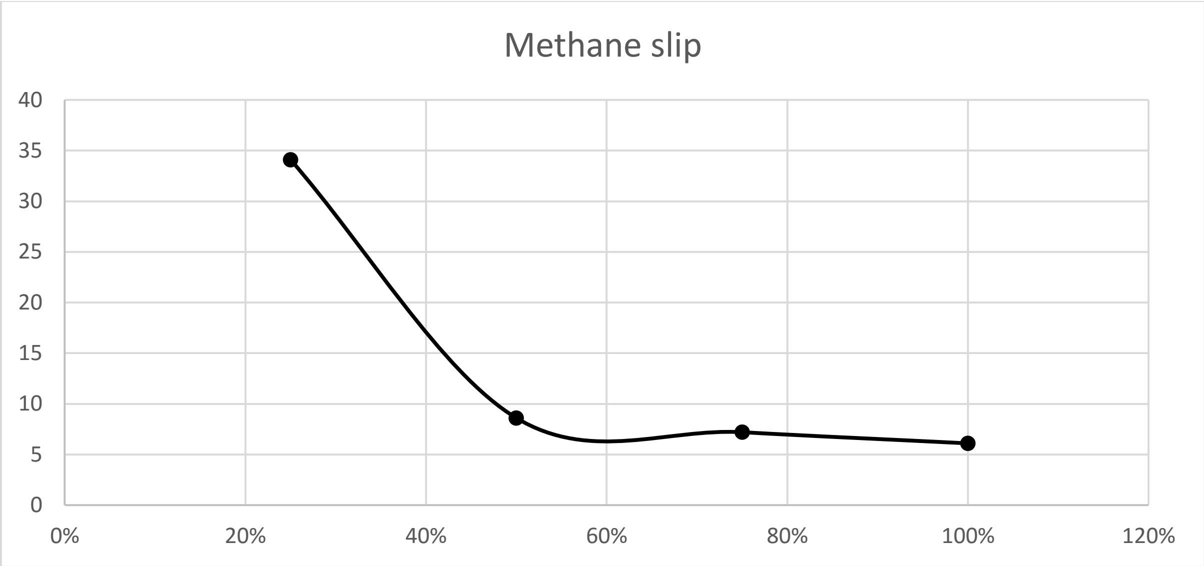
	MARINTEK	
PM 2,5	1,5	kg/ton
	9,86E-02	

CO	CF	0,00277	
	CO	1,82E-01	kg
CH4	CF	0,00006	
	CH4	3,94E-03	kg
N2O	CF	0,00015	
	N2O	9,86E-03	kg
NMVOC	CF	0,00308	
	NMVOC	2,02E-01	kg

MS Ampere Gas

Nox			
	marintek		
	kg Nox /ton LNG	5,6	
		2,57E-01	kg
CO_2			
	CF (t-CO2/t-Fuel)	2,75	MEPC
	CO_2		**ton**
		1,26E+02	**kg**
SO2,			
	CF (t-CO2/t-Fuel)	0,00002	
	SO_2	**9,18E-04**	**kg**
PM		0,00018	
		8,26E-03	kg
CO	CF	0,00783	
	CO	3,59E-01	kg

		25 %	50 %	75 %	100 %						
CH4	kg CH4/kWh	34,1	8,6	7,2	6,1						
	CH4										
%MCR	0,43930675		0,884336		0,75718492		0,2803677		0,439307		0,121429
#kWh during lifetime	1231903,98		3719783		54603100		1179310		1231904		4863786
g CH4/kW	14		6,5		6,9		27		14		39
	17246655,7		24178592		376761391		31841383		17246656		1,9E+08
total CH4	6,57E+08	g	1,82E+03	g							
	6,57E+05	kg	1,82E+00	kg							
	2,06566443										



Plot based on Methane factors ISO/IMO lean burn engines (SINTEF & MARINTEK, 2010).

N2O	CF	0,00011	
	N2O	5,05E-03	kg
NMVOC	CF	0,00301	
	NMVOC	1,38E-01	kg

Appendix E – Vector of Total Impacts Egalitarian and Individualist

D_tot per trip

Egalitarian	unit	EL-ferry	Conv	Gas	Diesel
Agricultural land occupation	m2a	5,12E-01	2,41E-01	5,97E-02	1,14E-01
Climate change	kg CO2 eq	6,25E+00	2,52E+02	1,63E+02	1,53E+02
Fossil depletion	kg oil eq	1,58E+00	8,23E+01	6,26E+01	5,01E+01
Freshwater ecotoxicity	kg 1,4-DB eq	4,34E-01	3,12E-01	4,85E-02	1,49E-01
Freshwater eutrophication	kg P eq	1,23E-02	8,05E-03	1,66E-03	4,37E-03
Human toxicity	kg 1,4-DB eq	9,31E+02	5,58E+02	9,80E+01	3,58E+02
Ionising radiation	kg U235 eq	1,73E+00	5,35E+00	5,31E-01	3,03E+00
Marine ecotoxicity	kg 1,4-DB eq	5,26E+02	3,82E+02	7,05E+01	1,82E+02
Marine eutrophication	kg N eq	4,28E-03	1,34E-01	1,26E-02	8,38E-02
Metal depletion	kg Fe eq	7,35E+00	7,35E+00	9,49E-01	1,03E+00
Natural land transformation	m2	3,16E-03	9,01E-02	3,73E-02	5,53E-02
Ozone depletion	kg CFC-11 eq	4,33E-07	3,79E-05	2,42E-05	2,33E-05
Particulate matter formation	kg PM10 eq	2,23E-02	3,48E+00	9,27E-02	2,14E+00
Photochemical oxidant formation	kg NMVOC	2,45E-02	4,79E+00	5,43E-01	2,98E+00
Terrestrial acidification	kg SO2 eq	5,53E-02	1,55E+01	2,83E-01	9,53E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	1,92E-01	4,50E-02	8,56E-03	2,57E-02
Urban land occupation	m2a	9,62E-02	4,29E-01	7,27E-02	2,54E-01
Water depletion	m3	2,39E+02	7,58E+01	9,56E+00	3,34E+01

Individualist	unit	EL-ferry	Conv	Gas	Diesel
Agricultural land occupation	m2a	5,12E-01	2,41E-01	5,97E-02	1,14E-01
Climate change	kg CO2 eq	7,23E+00	2,70E+02	3,06E+02	1,64E+02
Fossil depletion	kg oil eq	1,58E+00	8,23E+01	6,26E+01	5,01E+01
Freshwater ecotoxicity	kg 1,4-DB eq	4,12E-01	3,06E-01	4,78E-02	1,45E-01
Freshwater eutrophication	kg P eq	1,23E-02	8,05E-03	1,66E-03	4,37E-03
Human toxicity	kg 1,4-DB eq	9,90E-01	2,92E+00	5,03E-01	1,19E+00
Ionising radiation	kg U235 eq	1,23E+00	3,76E+00	3,77E-01	2,13E+00
Marine ecotoxicity	kg 1,4-DB eq	2,39E-01	2,61E-01	5,11E-02	1,08E-01
Marine eutrophication	kg N eq	4,28E-03	1,34E-01	1,26E-02	8,38E-02
Metal depletion	kg Fe eq	7,35E+00	7,35E+00	9,49E-01	1,03E+00
Natural land transformation	m2	3,16E-03	9,01E-02	3,73E-02	5,53E-02
Ozone depletion	kg CFC-11 eq	4,33E-07	3,79E-05	2,42E-05	2,33E-05
Particulate matter formation	kg PM10 eq	2,23E-02	3,48E+00	9,27E-02	2,14E+00
Photochemical oxidant formation	kg NMVOC	2,45E-02	4,79E+00	5,43E-01	2,98E+00
Terrestrial acidification	kg SO2 eq	5,08E-02	1,47E+01	2,13E-01	9,07E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	6,79E-03	1,50E-02	2,86E-03	9,05E-03
Urban land occupation	m2a	9,62E-02	4,29E-01	7,27E-02	2,54E-01
Water depletion	m3	2,39E+02	7,58E+01	9,56E+00	3,34E+01